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CH-47C VULNERABILITY REDUCTION MODIFICATION PROGRAM - FLY-BY-WIRE BACKUP DEMONSTRATION

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EUSTIS DIRECTORATE POSITION STATEMENT

This report of a laboratory test program demonstrates a survivable design technique to provide a redundant flight control system for an existing helicopter. The program consisted of the application of a single-channel fly-by-wire (FBW) system, with a CH-47C helicopter mechanical flight control system as a backup. This redundant system is designed to operate automatically full-time with built-in protection against open failures of either control system. Pilot action is not required to engage the FBW backup in the event of 23mm explosive ballistic projectile damage to the existing mechanical system. Results of this contractual effort demonstrated that the system was feasible without interfacing problems or degradation of aircraft performance in the event of failure of either control system. However, additional effort is required to define the details of a projected production configuration.

Mr. Stephen Pociluyko of the Military Operations Technology Division served as the Technical Monitor for this effort.

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The purpose of the work performed was to accomplish a laboratory demonstration of a fly-by-wire (FBW) backup flight control system for application to the CH-47C helicopter. Tests, evaluations, and an analysis were conducted to determine the feasibility of using an electrical linkage as a backup to the existing mechanical flight control system. Of primary concern was the interfacing technique between the two systems,

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which was to result in no degradation of control system performance during normal operation and which would permit safe operation of the aircraft in the event of a failure in either the mechanical or the FBW backup system. The program was performed in four tasks. Task I involved the definition of a FBW backup system based on use of HLH ATC components suitable to demonstrate concept feasibility on the Boeing "Iron Bird" flight control test rig. Task II involved the modification and installation of the system on the test rig with the actual testing and performance evaluation being conducted during Task III. Task IV effort involved the reassessment of effects analysis conducted under Contract DAAJ02-74-C-00[illegible].

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SUMMARY

The feasibility of a single-channel FBW linkage operating in parallel with the existing mechanical system between the lower and upper boost actuators was demonstrated. The key to the system's operation was the choice of a low gain differential pressure feedback used in conjunction with mechanical system compliance to take up tracking errors between the system. Important findings of this study beyond the feasibility of demonstration include:

1. The FBW backup system does not degrade the mechanical system performance and in some cases enhances mechanical system performance.

2. Conservative failure testing substantiates that in all cases MIL-H-8501A failure requirements are met.

3. There is the desirability of automatic shutdown after a 3-4 sec. delay to minimize the effects of a passive FBW actuator failure.

4. An elimination of CH-47C lower boost actuators would be undesirable.

5. The system is totally passive and requires no pilot action to have protection available.

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INTRODUCTION

This study was conducted in support of the Aircraft Survivability Equipment (ASE) Required Operational Capability (ROC). As stated in the ROC, the ASE is needed for the CH-47C to perform its planned missions by increasing its combat effectiveness through reduction of the enemy's ability to hit, damage, or destroy the CH-47C helicopter. Prior Government analysis and contractor effort identified a fly-by-wire (FBW) backup control system as a potentially effective concept for reducing the ballistic vulnerability of the helicopter.

The purpose of the work performed under this contract was to accomplish a laboratory demonstration of a fly-by-wire backup flight control system for application to the CH-47C helicopter. Specifically, tests, evaluations, and an analysis were conducted to determine the feasibility of using an electrical linkage as a backup to the existing mechanical flight control system. Of primary concern was the interfacing technique between the two systems which must allow no degradation of performance during normal operation of the control system, and must permit safe operation of the aircraft in the event of a failure in either the mechanical or the FBW backup system.

A FBW backup control system meeting program objectives was demonstrated. The concept is feasible for installation on the CH-47C helicopter. Control system performance and ballistic protection requirements can be met. The system defined under contract was installed and evaluated on Boeing's "Iron Bird" test stand with results substantiated in this document. Some areas of further development are defined in this document which will require additional effort to define details of final production configuration.

CH-47C VULNERABILITY REDUCTION MODIFICATION PROGRAM, FLY-BY-WIRE BACKUP DEMONSTRATION

The CH-47C Vulnerability Reduction Modification Program, Fly-By-Wire, was divided into four task elements. The required items for each of the tasks were as follows:

TASK I - FUNCTION AND CHARACTERISTICS INVESTIGATION

1. FBW System Function Requirements and Characteristics Definition.
2. FBW Schematics and/or Block Diagrams.
3. Interface Technique Definition.
4. ATC DELS System Modification and Definition.
5. "Iron Bird" Test Rig Modifications.
6. Test Plan.

TASK II - SYSTEM INSTALLATION ON TEST RIG

1. Modify "Iron Bird"
2. Modification and installation of one channel of existing HLH ATC DELS.
3. Functional checkout of systems.

TASK III - TESTING AND PERFORMANCE EVALUATION

1. Testing to determine the operational characteristics of the mechanical system for use as a baseline (FBW backup disconnected).
2. Testing to determine the performance characteristics of the flight control system with the FBW backup connected, using the various interfacing techniques investigated in Task I, above.
3. Testing to determine the failure performance of the system for open mechanical linkage before and after the mix, and for passive and hardover failures of the FBW backup system. Failure transients calculated to be in excess of the limits described in MIL-H-8501A shall be defined, flight safety criticality determined, and rationale presented.
4. An analysis of the results shall be made, the best interfacing technique determined, and the rationale presented.

5. Testing to determine the effects of depressurizing and bypassing lower boost actuators on normal operation and on FBW failed operation. Results shall be analyzed to determine the effects on flight control system performance and flight safety relative to a FBW failure with no lower boost in the mechanical control system.

TASK IV - SYSTEMS ASSESSMENT

1. Qualitative assessment of results to include:

   a. Identification of any major deficiencies/problems relative to potential development.

   b. Reliability.

   c. Maintainability.

   d. Development.

   e. Qualification.

   f. Availability.

   g. Cost.

This report discusses each of these areas and is arranged in the order cited.

FUNCTION AND CHARACTERISTICS INVESTIGATION

FBW SYSTEM FUNCTION REQUIREMENTS AND CHARACTERISTICS DEFINITION

The following requirements have been established as the basis for the FBW backup system.

1. The function of the backup FBW system is to duplicate the capability of the mechanical system from lower boost actuator output to upper boost actuator input (including SAS functions). The system provides protection for open failures in this area.

2. In accomplishing this function, the backup system shall not degrade the performance of the linkage below that provided by the mechanical system.

3. Failures of the backup system or the mechanical system shall not degrade the flight safety of the aircraft. Normal acceleration, angular velocity, and allowable pilot delay on failure shall meet the requirements of MIL-H-8501A.

4. Jam failures of the FBW actuator shall not result in jamming of the upper boost actuator. Jams in the actuator shall be cleared by a suitable latching disconnect device. Once disconnected, the actuator shall impose negligible (less than 5 lb.) loads on the upper boost actuator input. Reset of the disconnect shall be by manual actuation of the reset lever located at the disconnect.

5. Failure of the system shall not require a mission abort; operation in hazardous combat areas without the backup should be up to the discretion of the using agency. If inoperative, the system shall be disengaged automatically or by pilot action in response to a failure display.

6. The system shall operate full time unless disengaged and shall not require pilot action to achieve protection for open failures.

7. Upon installation of the backup system, anti-jam devices such as described in Boeing Vertol Document D210-10991-1 should be taken to reduce the chance that open failures could result in jamming of the mechanical control runs. Figure 1 shows the proposed method of retaining control rods at points where they pass through structure. (It is

recommended that these methods be included in the cost of installation of the backup system.)

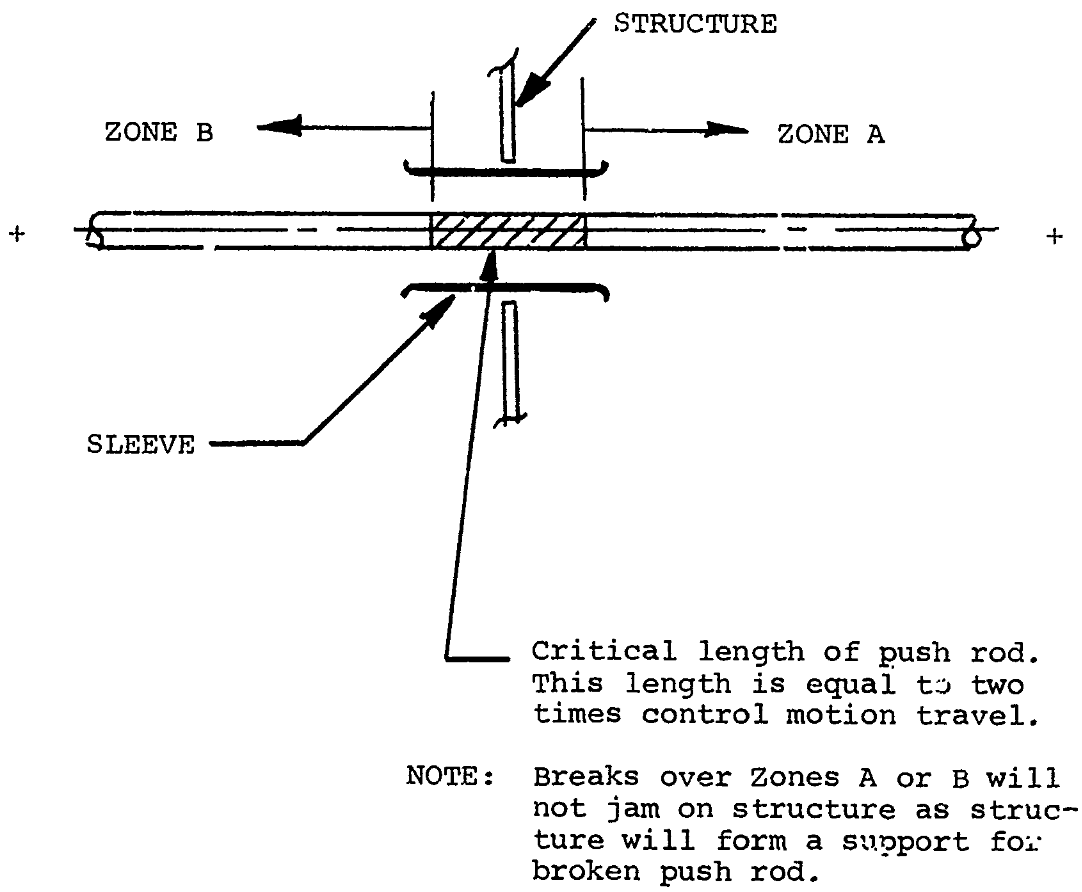


FIGURE 1. CONTROL ROD RETENTION CONCEPT

FBW SCHEMATICS AND/OR BLOCK DIAGRAMS

The system under test is a modification of the triplex direct electrical linkage system tested as part of the HLH Advanced Technology Component Development Program. The system was tested on the "Iron Bird" and test flown for 315 hours in the Model 347 helicopter to demonstrate concepts to be used in the HLH. Figure 2 shows a block diagram of the system as installed and tested on the "Iron Bird" test stand.

Mechanical Path

One axis of pilot control is shown on Figure 2 as it passes through the mechanical mixer and fans out to control the forward and aft rotors via upper boost actuators. The complete system accepts longitudinal, lateral, directional and collective pitch control.

Each cockpit control operates each upper boost actuator via the mechanical mixer. For example, if the pilot increases collective pitch, all four upper boosts extend. If he puts in right lateral stick (commanding a rolling maneuver), the forward and aft left-hand actuators extend while the right-hand actuators retract.

The upper boost actuators control the blade pitch by inputs to the stationary swashplate, which, in turn, positions the rotating swashplate which drives the blade pitch change linkage.

Pilot input to the mechanical mixer is via the lower boost actuator. The lower boost reacts friction loads in the mechanical system and prevents forces generated by motions of the Stability Augmentation System (SAS) actuators from feeding back to the pilot controls. The lower boost is supplied from two hydraulic sources.

The SAS actuator accepts signals from the SAS electronics unit and produces motions appropriate to damp external disturbances and stabilizes aircraft rate and sideslip response. The actuator is dualized, consisting of two identical units bolted together. The actuator forms part of the series linkage at the output of the lower boost and is called an "extensible link". Dual actuators are normally installed in the longitudinal, lateral, and directional control axes. In collective pitch, there is a control rod in place of the actuator.

For convenience in setting up the system for demonstration in the program, single actuators were installed in the longitudinal and directional axes only. These two axes span the range of control sensitivity. Longitudinal is the least sensitive axis (upper boost motion/stick motion is approximately 1/10), while directional is the most sensitive (upper boost motion/pedal

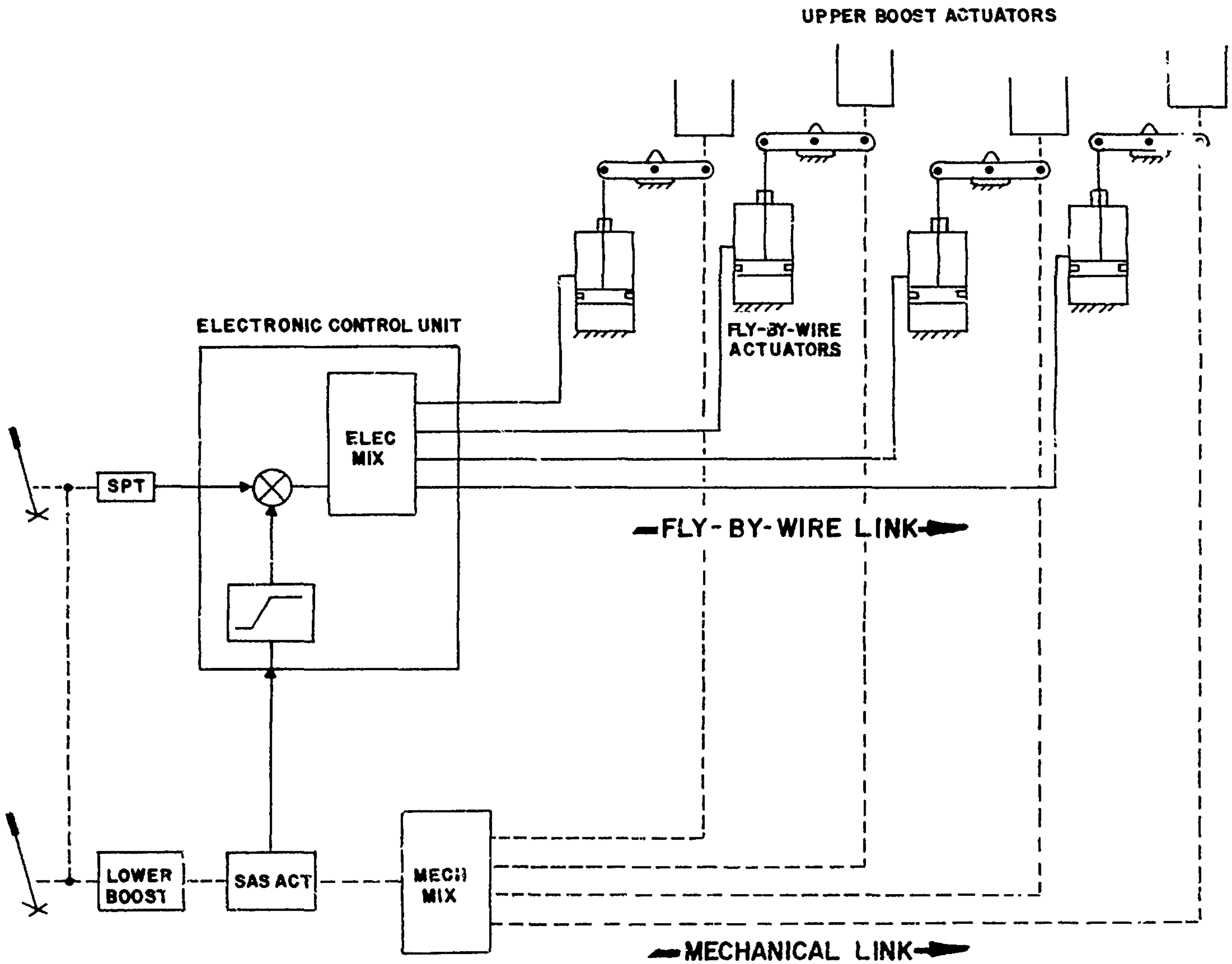


FIGURE 2. CH-47C BACKUP FLIGHT CONTROL SYSTEM-BLOCK DIAGRAM

motion is approximately 1/1). Operation on single system is adequate to demonstrate interfacing of the SAS with the backup fly-by-wire system.

Electrical Path

The electrical path begins at the Stick Position Transducer (SPT) which is attached to the cockpit control linkage. The transducer is a Linear Variable Differential Transformer (LVDT) which is excited with 26 VAC, 1800 Hz and produces an AC output proportional to control displacement. In the existing HLH ATC system, the transducers were located in the heater compartment aft of the pilot's station. For fly-by-wire the output to the mechanical system was disconnected at the lower boost input. For a production fly-by-wire backup, the SPT would be mounted on the lower boost actuator where it could be protected by the same armor necessary to protect the lower boost.

The additional linkage imposed by the 347 configuration posed a more difficult problem in achieving system tracking because looseness and deflection of this linkage (particularly on stops) causes mistrack between the two systems. Therefore, tracking results of the demonstration will be conservative relative to that achieved in production.

The Electronic Control Unit (ECU) accepts signals from SPT and from the SAS. It performs the same mixing functions as the mechanical mixer. It also performs the function of the SAS actuator (namely, summation of SAS and pilot command motions).

Motions of the SAS actuator are used to generate the SAS inputs to the fly-by-wire. Signals produced by a position feedback LVDT on each of the actuator sections are intercepted and sent to the ECU as well as to the SAS. The signals are received on balanced buffer inputs to preclude interaction of the systems which could affect SAS performance.

Actual SAS actuator motions were selected for the fly-by-wire input rather than the actuator command signals so that tracking of the systems would not be compromised by the SAS actuator's failure to respond to input command. An erroneous shutdown of fly-by-wire could occur if the SAS actuator failed to respond while the fly-by-wire did. Under the selected arrangement, the fly-by-wire exactly tracks the SAS even subsequent to SAS failure.

A second major function of the ECU is to control the fly-by-wire actuators which form the output of the backup channel. In production, these actuators would be connected at the final bellcrank driving the upper boost input.

The functions of the ECU are more fully described in the following detail diagrams.

Mixing--Figure 3 shows details of the interface with the SPT, SAS and mixing. Functions shown are those present in the ATC hardware. Axis and cumulative lateral limits are analogous to those found in the mechanical system.

The longitudinal inputs are dualized. This is necessary so that failures can be detected without need to develop forces between the electrical and mechanical linkages. Failure testing, discussed in a later section, shows that deflections caused by longitudinal axis failures could be excessive relative to failure acceptance criteria. The reason deflections are critical for longitudinal axis is its low sensitivity. Full stick travel amounts to $\pm.6$ in. of upper boost travel; mechanical system deflections can be a significant part of that travel.

The various axes command signals are summed at the actuator mixer amplifiers; the output ot the amplifier represents the actuator position command signal.

Servo Loop--Figure 4 shows how the command is used to control actuator position.

In the HLH ATC, the signal path from input to servo actuator command was dualized so that there was an active and model servo loop card. The two cards shown in Figure 4 represent the parts of the two cards retained for the backup system. The former "active card" (now "servo") includes the elements used to control the actuator while the former "model card" (now "logic") contains the elements necessary for failure monitoring. In production, the functions shown would be incorporated on a single circuit card. The ECU would contain four identical cards.

The servo card accepts an input from the mixer and sums it with a signal from the actuator ram position LVDT to form a position error signal. When the actuator ram equals the commanded position, the summed output is zero. The position error signal is passed to the servo amplifier where it is summed with the output of the differential pressure transducer.

The differential pressure transducer measures the output force of the actuator and is used to modify the stiffness of the actuator and to detect force fights between the mechanical and electrical paths. Details of the failure detection will be discussed later. (See Figure 5.)

The servo amplifier output is a current signal which positions the two-stage, Electro-Hydraulic Valve (EHV) spool in a proportional manner. The EHV controls hydraulic fluid to the actuator ram in proportion to its spool position. The ram output velocity, in turn, is proportioned to its

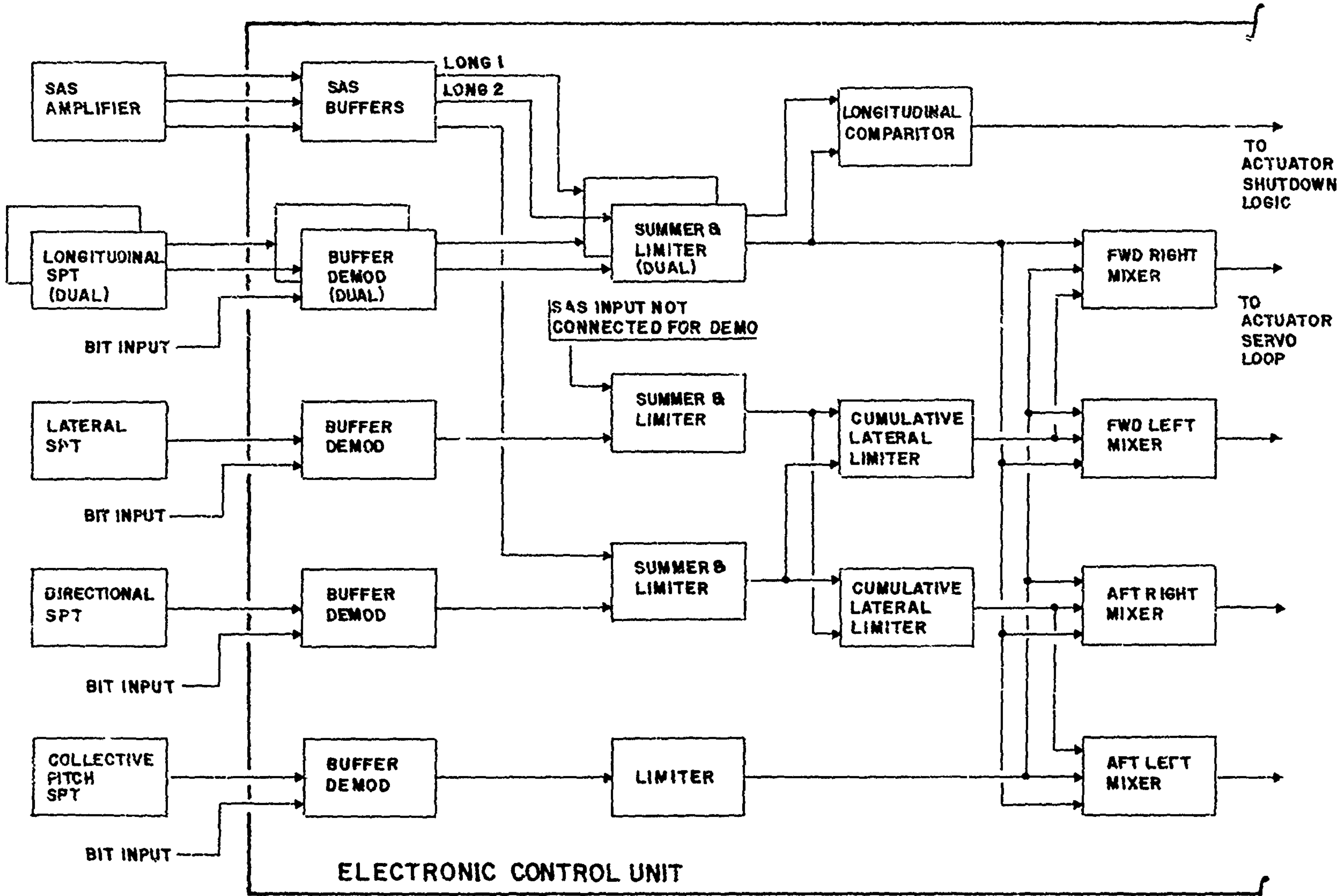


FIGURE 3. CH-47C FLY-BY-WIRE BACKUP: INPUT INTERFACE AND MIXING BLOCK DIAGRAM

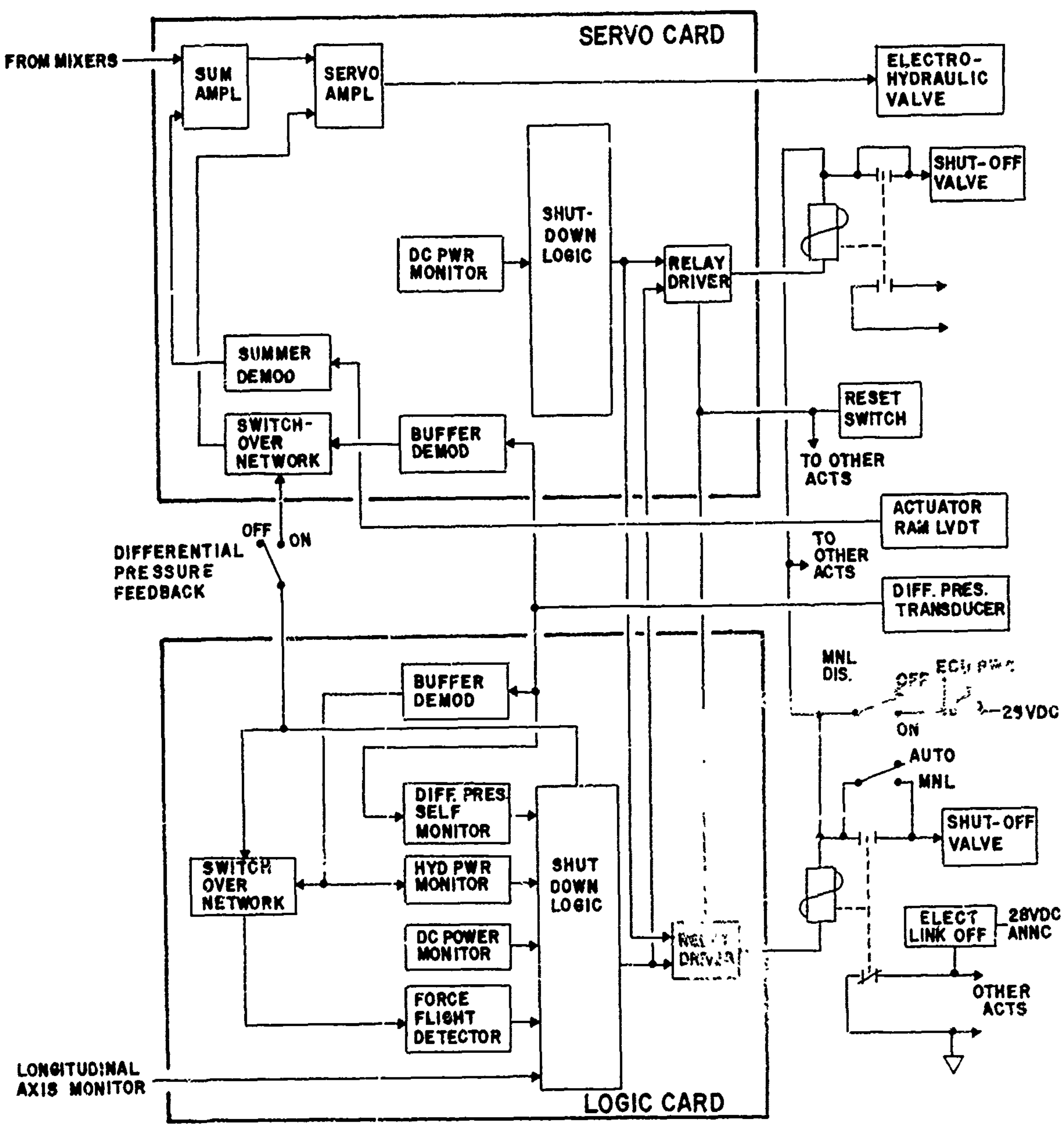


FIGURE 4. SERVOLOOP INTERFACE DIAGRAM

input flow. The result is that ram velocity is proportional to servo amplifier current output.

The two-stage electro-hydraulic valve pressure response is normally very abrupt. If the ram is stalled, a small change in input current will produce a large change in output pressure. This high pressure gain means that a small error between the two systems could result in a full pressure force disparity.

The differential pressure signal is used to modify the actuator pressure gain by negative feedback. Figure 6 shows the effects of the feedback. If EHV output pressure tries to change, the transducer sends back a signal which subtracts from the input. It takes more input to produce the same valve command; therefore, the pressure gain is reduced.

Actuator Control Logic--All failures that require shutdown of the actuator make inputs to the shutdown logic. The logic output acts via a relay to supply 26 VAC power to the hydraulic shutoff valve. Power is maintained on the valve in the absence of a failure. The ATC system employed dual shutoff valves which were connected hydraulically in series; loss of power to either valve would remove hydraulics from the actuator. Dual valves were used to provide a high probability of removing hydraulics from all three systems simultaneously if reversion to mechanical backup was required. In the backup fly-by-wire, a single shutoff valve will provide adequate performance.

For the test program, shutoff of the valve driven by the servo card was prevented by jumpering the control relay. Shutoff via the second valve was controlled by the manual/auto disengage select and via the manual ON-OFF switches. These switches allowed evaluation of automatic versus manual shutdown in the presence of system failures.

The system is reset by momentarily overriding the shutdown logic. This allows hydraulics to be reapplied to the actuator and if no failures are present, it will remain engaged; otherwise, it will shut down again. The length of the reset pulse is approximately 0.150 second.

Failures in the electrical path are detected primarily by monitoring of differential pressure at the actuator. If the systems track perfectly, there would be no steady-state force output from the actuator. To the extent that the systems mistrack, there will be a steady-state force output. The mistrack then is a measure of the performance of the electrical system. The amount of mistrack allowed depends on the spring rate of the mechanical system and the differential pressure gain of the fly-by-wire actuator.

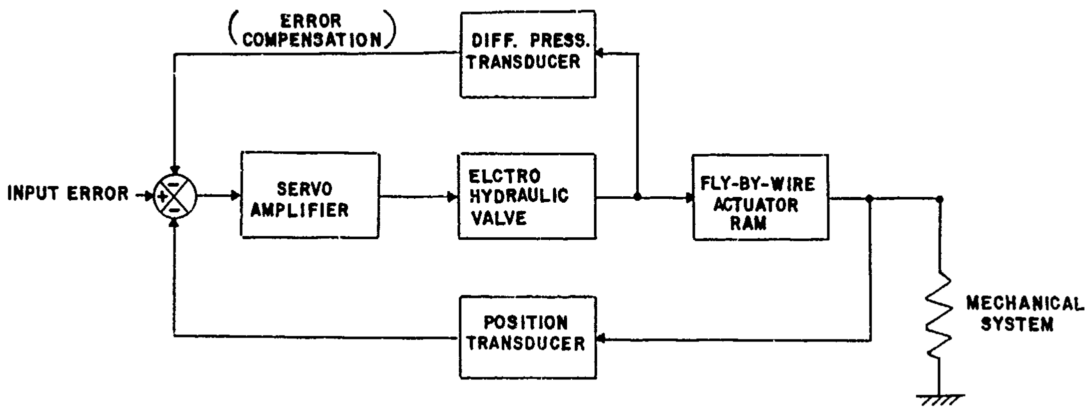


FIGURE 5. SERVOLOOP BLOCK DIAGRAM SHOWING EFFECT OF PRESSURE FEEDBACK

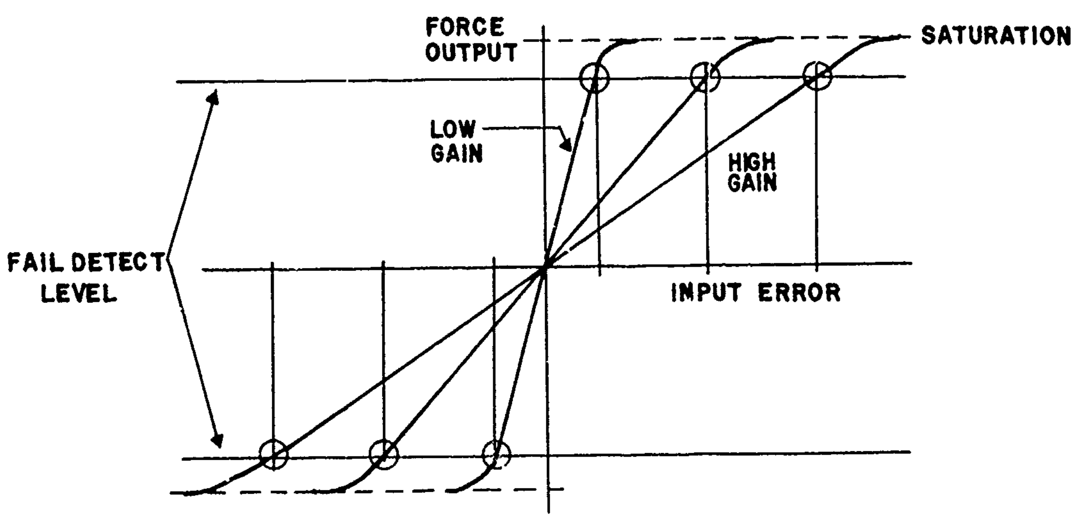


FIGURE 6. VARIATION OF FORCE OUTPUT WITH DIFFERENTIAL PRESSURE FEEDBACK GAIN

A failure is declared when the steady-state pressure reaches a level slightly below the saturation force output of the actuator. Figure 6 shows how varying the differential pressure feedback gain and reducing force output gain can allow for more error.

(Reducing the actuator output force characteristic, however, has the undesirable characteristic of increasing the hysteresis effect in the actuator output characteristic. The actuator is, in effect, driving through a spring characteristic as shown in Figure 7. When driving against a friction load, the spring must deflect enough to overcome breakout friction; this results in a hysteresis effect in the output.)

Because of criticality of longitudinal axis, dualized inputs are compared, and if the difference exceeds a prescribed threshold, the actuators are shut down.

Since the differential pressure transducer is the basic input to the force fight monitor, its failure could result in inability to detect subsequent force fights. Its output LVDT is monitored for shorts, opens, or loss of excitation by a self-monitoring scheme used in the HLH ATC system.

Figure 8 illustrates the method used. The LBDT secondary winding voltages are summed and passed through a threshold circuit. If operation is normal, the sum of the secondary voltage should be constant regardless of LVDT position. If the LVDT has an open or short to ground, the output will go down; if it has a short to power, the output will go up. Whenever the sum voltage deviates from the range allowed by normal tolerances, the associated actuator is shut down. The scheme also serves as a monitor for AC power to the ECU and connection of electronic control unit and FBW actuator cabling.

The presence of each derived box power supply is checked where its failure does not cause direct shutdown of the actuator.

The hydraulic power supply monitor provides two functions:

1. It indicates that the actuator has lost hydraulic power for some reason. It could be a supply failure, line failure, loss of drive to the shut valve or valve internal failure.

2. It provides a latch so that after shutdown for any failure, the system cannot reengage without pilot action to reset. This means that if there is a transient failure, the system cannot keep cycling on and off.

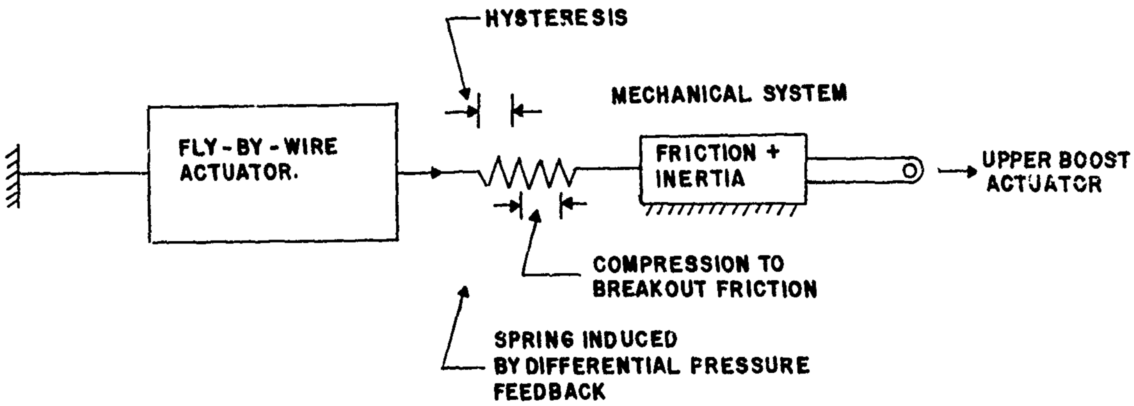


FIGURE 7. FLY-BY-WIRE DRIVING THROUGH SPRING RATE OF ACTUATOR

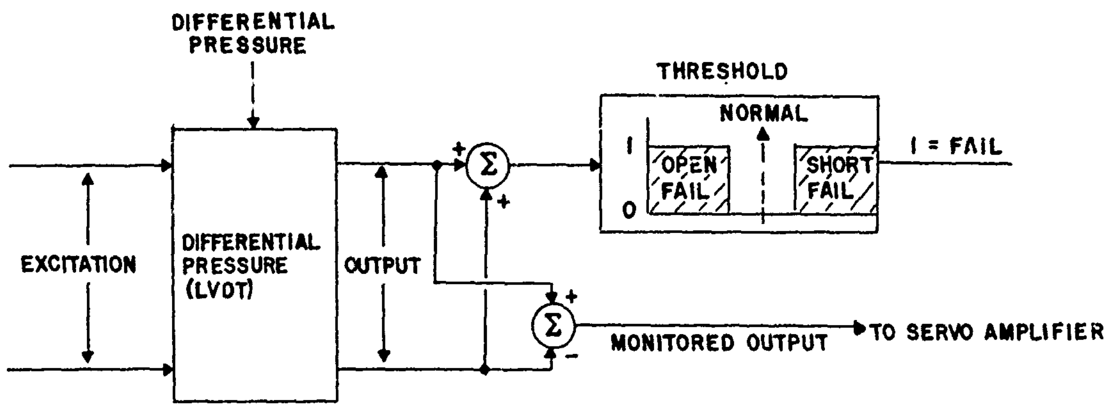


FIGURE 8. DIFFERENTIAL PRESSURE TRANSDUCER SELF-MONITOR

In the ATC hardware, loss of pressure was indicated by driving the differential pressure hardover with a spring force which was balanced by hydraulic pressure when it was applied. The hardover condition was beyond the normal range of operation with pressure on, so that a definite indication of pressure loss could be obtained. The ATC transducer also incorporates a valve to bypass the RAM cylinders when pressure is lost.

Auxiliary contacts on the shutdown control relay are used to operate the lamp indicating ELECT LINK FAIL on the control panel. In production, a second lamp integral with the engage-disengage switch will indicate system off.

Failure Detection Built-In Test--Means used to detect active failures of the backup fly-by-wire and its power supplies were described in the previous section. To assure that these detectors are not themselves failed, it is necessary to test them periodically by inducing system failures and noting that the failure detection can properly detect these shutdowns and latch the appropriate actuators.

This function is accomplished by the built-in-test capability of the ECU. For the demonstration system, manually operated inputs were provided to stimulate the force fight detector, the longitudinal comparitor, and the differential pressure LVDT self-monitor; operation of the manual inputs causes shutdown, and operation of the hydraulic pressure loss detector is noted by the continuation of shutdown when the original stimulus is removed.

Formal test of the DC power monitor is not necessary since it involves components whose failure would result in a shutdown; secondarily, they are so simple that the adding of components to check would be counter-productive.

INTERFACE TECHNIQUE DEFINITION

Two basic techniques are available to take up errors between the mechanical and fly-by-wire backup systems during normal operation.

Mechanical Slaved to Electrical (Figure 9)

Errors may be absorbed in the spring rate and backlash of the mechanical system. For this case, the fly-by-wire output spring is made very stiff, and the fly-by-wire controls the upper boost position within the limits allowed by mechanical system compliance. This approach will give the best system fidelity since the effects of spring rate and backlash in the mechanical system will be eliminated; overall response can be improved. Note that springs have been added to the existing system to preload out the backlash. These springs were added

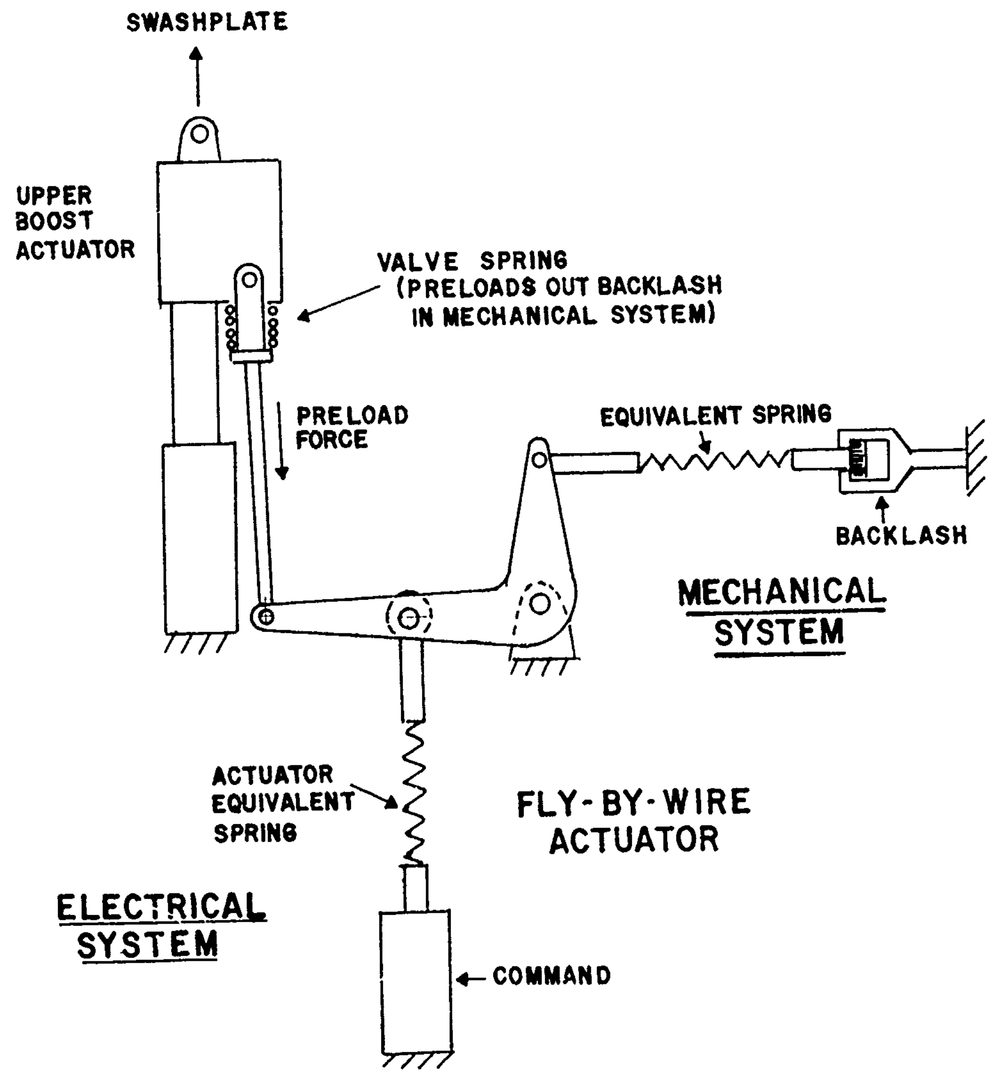


FIGURE 9. MODEL OF MECHANICAL SYSTEM/ELECTRICAL SYSTEM SPRING AND BACKLASH CHARACTERISTICS

on the CH-47B when the pitch attitude stabilization function was introduced. With attitude stabilization loops operating, the backlash in the existing mechanical system caused a limit cycle oscillation in the pitch axis.

This method is limited by the spring rate of the mechanical system (approximately 300 lb/in. at the boost input), and by the allowable output force of the fly-by-wire actuator. For example, if a force limit of 50 lb is selected, the allowable mistrack would be .167 in. If this displacement is not sufficient, either the mechanical system must be further softened or the second approach must be used.

Electrical Slaved to Mechanical (Figure 9)

The second approach available is to introduce compliance in the electrical path. This may be accomplished by using differential pressure feedback or by introducing a spring in series with the fly-by-wire actuator output. Depending on the level of the spring rate, this method degrades the performance improvement that can be achieved with electrical control as the primary control. In addition, the spring characteristic will be present for the open condition.

The method selected for the demonstration system employs the differential pressure feedback available in the ATC hardware. Investigations were made with no differential pressure feedback and with feedback at various gain levels. The objective was to achieve acceptable static and dynamic performance while maintaining force fights at a level to prevent nuisance disengagements.

Another part of the system investigation centered on the need to shut down following failure of the system. Criteria used for judging the need to shut down included: failure transient magnitude and control limitations with a failure present.

ATC DELS SYSTEM MODIFICATION DEFINITION

Changes to the ATC DELS were those determined to be necessary to reconfigure the system to the configuration defined in previous sections of this report. These changes included the following items:

1. Eliminating failure monitors no longer required.

2. Creation of the force fight detector from available circuitry.

3. Provision for changing differential pressure feedback gains and switching feedback on and off.

4. Provision to allow selection of automatic or manual shutdown on failure.

5. Provision for built-in-test inputs.

6. Provision for SAS inputs.

Modifications were accomplished by General Electric Aircraft Equipment Division (the original manufacturer of the equipment).

To limit costs, the existing swashplate driver actuators were not modified, although it should be recognized that their friction is higher (because they are triplex) than could be achieved with a production design. The residual friction tends to degrade performance for the fly-by-wire with differential pressure feedback and fly-by-wire disengaged case; therefore, results achieved will be <u>conservative</u> relative to expected production configuration.

Another limitation of the existing swashplate driver actuator (SDA) is that pressure measurement is limited to ±200 ±50 psi; therefore, the force fight failure detect level must be limited to the measurable range. This limitation meant that the failure detect level was set lower than would be necessary in production, making nuisance trips more likely.

<u>IRON BIRD TEST RIG MODIFICATIONS</u>

At the start of the backup demonstration program, the flight control test rig (Figure 10) was configured for pure fly-by-wire operation, except that some of the triplex system cables had been removed to support fabrication of the HLH prototype test stand. A detailed description of the test stand can be found in Boeing Vertol Document D301-10199-1. Areas of activity to reconfigure the test stand included:

1. Reconfigure and reinstall one channel of system wiring as shown in Figure 11. The test control panel and interface with the SAS were the major changes. (Details are in Appendix F.)

2. Modify the test stand to provide for installation of the control unit and panels (Figures 12 and 13). The existing DELS preflight test set, which provides access to the system parameters, was installed along with the original DELS status panel (modified for single channel operation). All necessary circuit breakers and switching were consolidated at the side of the stand.

3. Reinstall and wire a single SAS system including single actuators in longitudinal and directional axes.

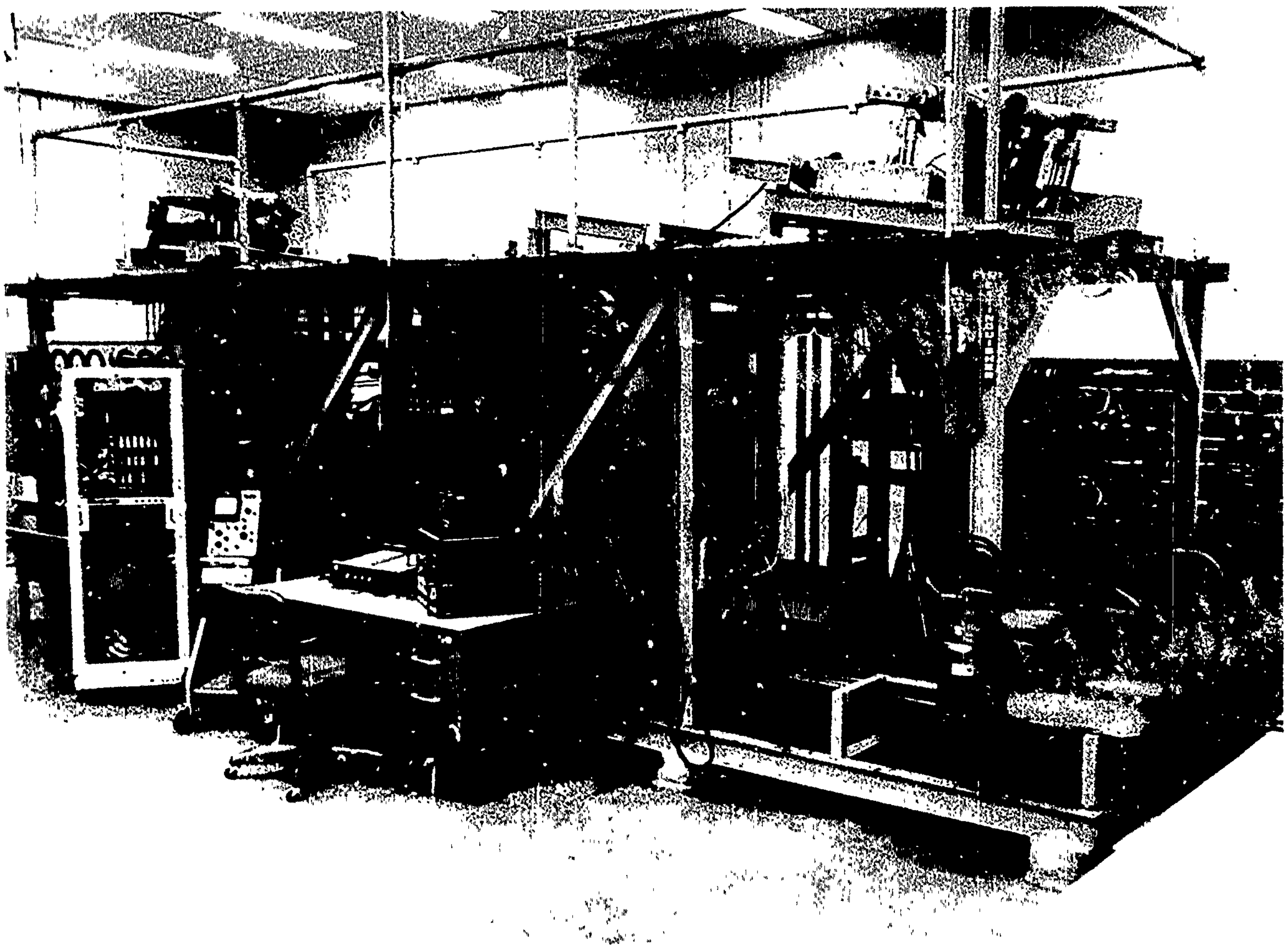


FIGURE 10. FLIGHT CONTROL TEST RIG

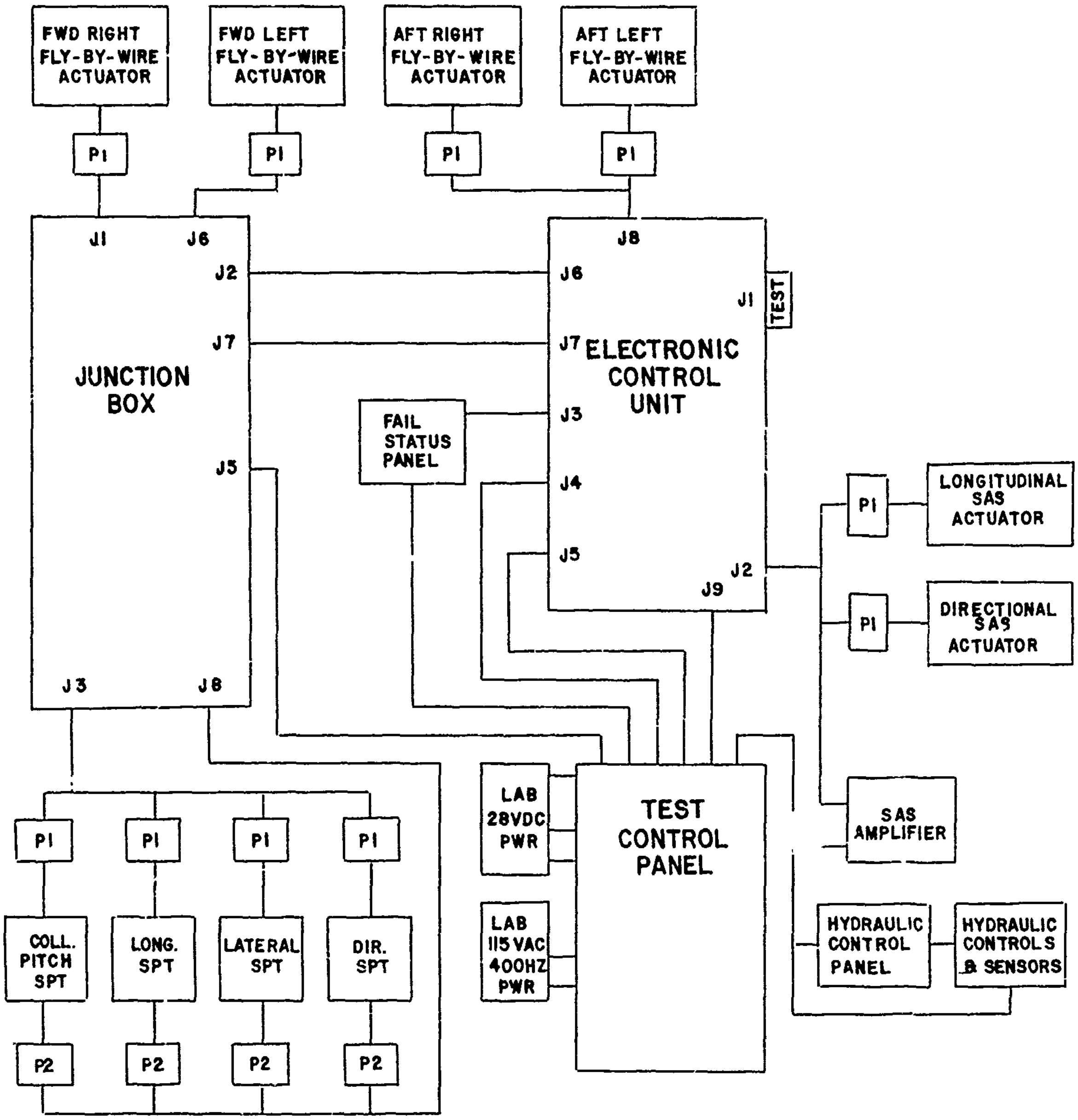


FIGURE 11. DEMONSTRATION SYSTEM INTERFACE DIAGRAM

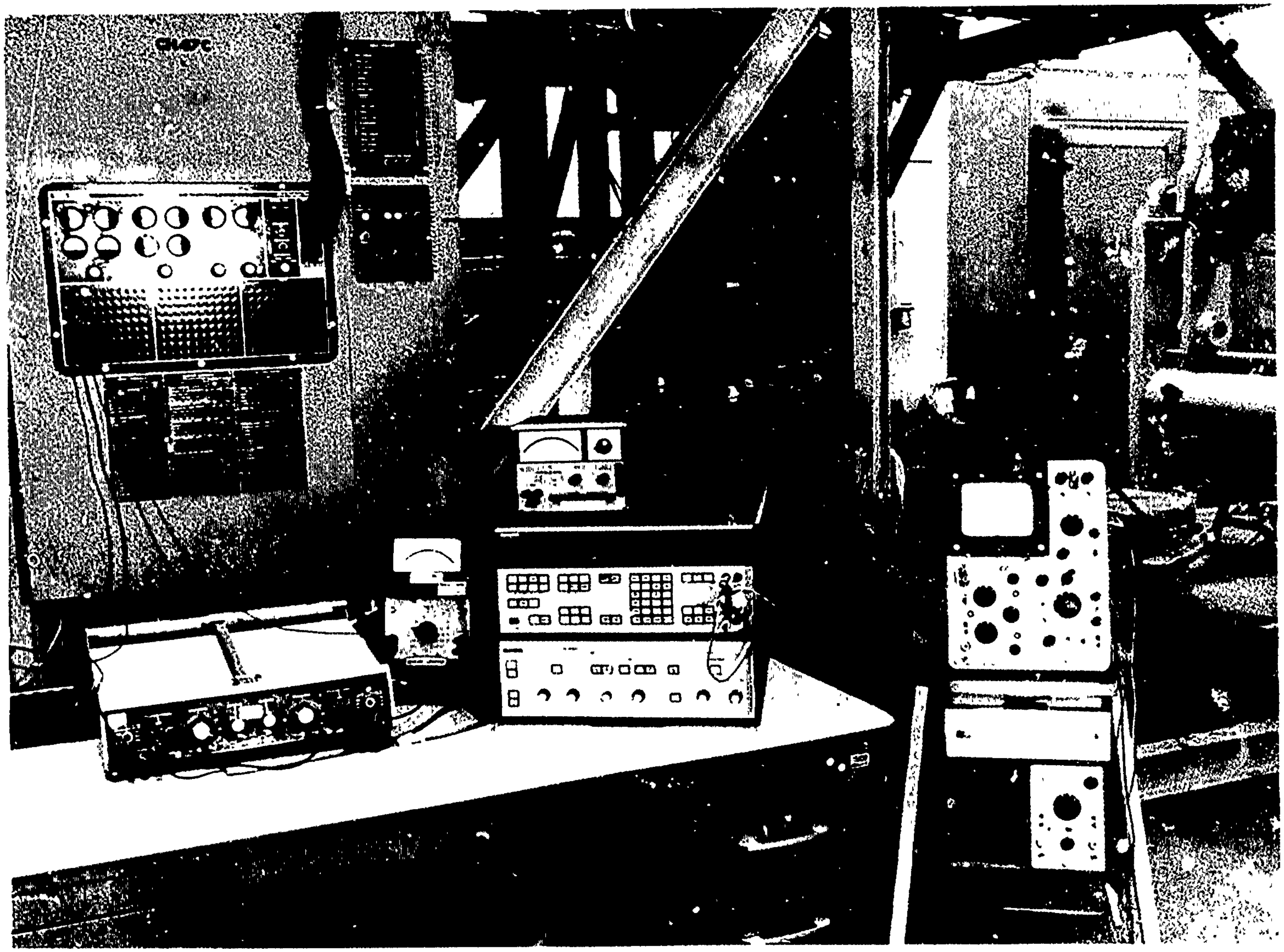


FIGURE 12. SIDE OF STAND

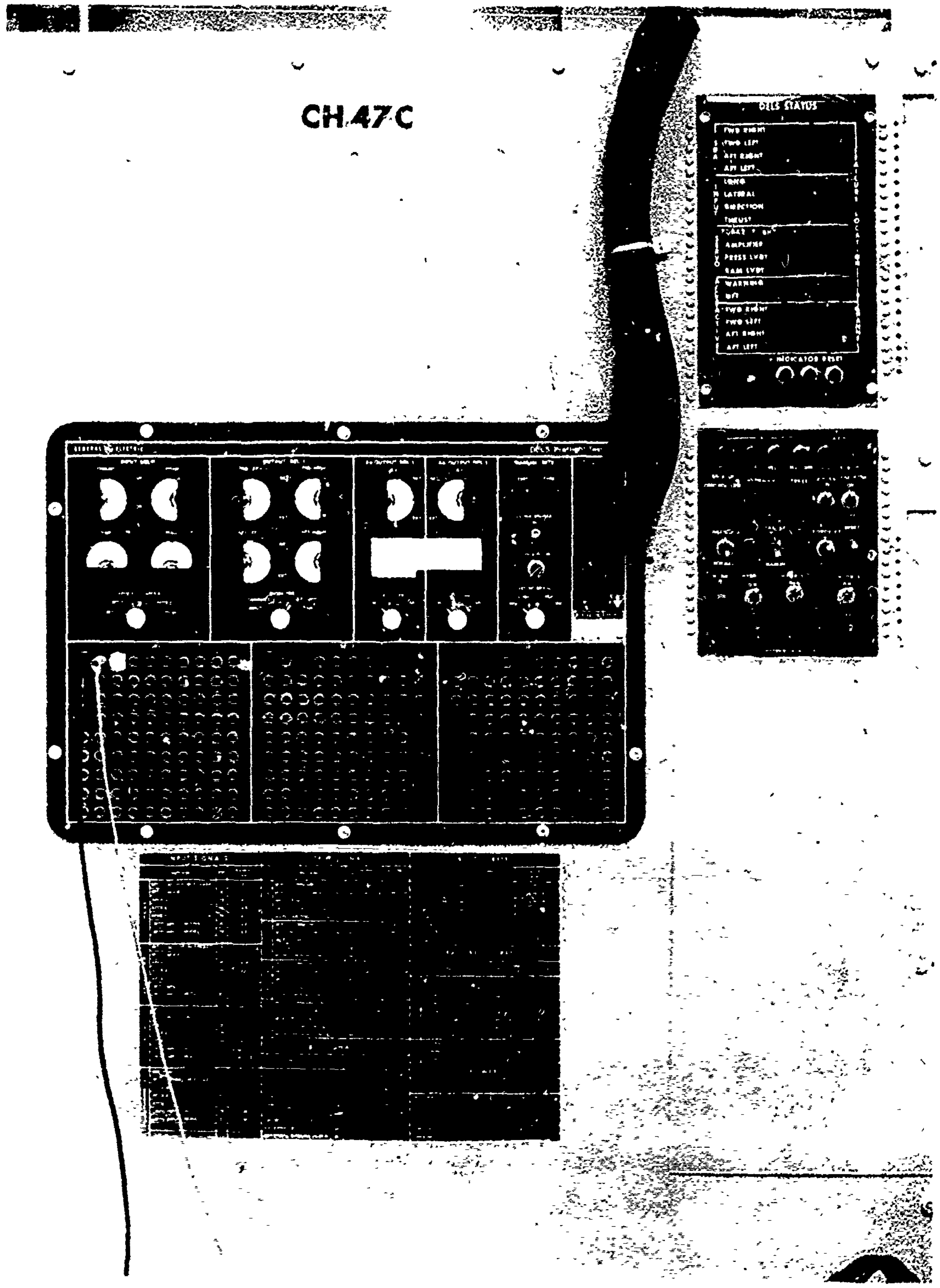


FIGURE [illegible]. VIEW OF SIDE PANEL

4. Reconnect the mechanical linkages at the lower boost actuator input and at the swashplate driver actuator input.

5. Reactivate and recalibrate upper boost position measuring instrumentation. Other system parameters were available at the DELS preflight test set.

6. Connect the swashplate driver actuator to hydraulic channel 3 and reduce system inlet pressure to 750 psi (Figure 14). Reinstall hydraulic system components which had been removed to support fabrication of the HLH Prototype test stand. System pressure was reduced so that the mechanical system could overcome FBW failures. The level selected was compatible with proper operation of the system electrohydraulic valve; however, the resulting actuator output force was higher than that compatible with a directional axis hardover; actuator force will be reduced for production (93 lb versus 50 lb). For this reason, all failure results are conservative.

TEST OUTLINE

The required outline entitled, "Test Outline, CH-47C Fly-By-Wire Backup Demonstration (Laboratory)", dated October 6, 1975, is reproduced in Appendix A, with principal sections outlined below.

Mechanical System Checkout

Balance cockpit controls, check force feel and check for friction in the mechanical system.

Stability Augmentation System Checkout

Check per normal response to test inputs. Check interface with fly-by-wire for gain and phasing.

Electrical Linkage Functional Checkout

Engage fly-by-wire, check for normal response to inputs and built-in-test. Adjust tracking with mechanical system. Record baseline mechanical system data.

Electrical/Mechanical Performance Evaluation

Take data with and without differential pressure feedback gain and shaping. Evaluate response to failures. Select most desirable system configuration. Demonstrate system to customer.

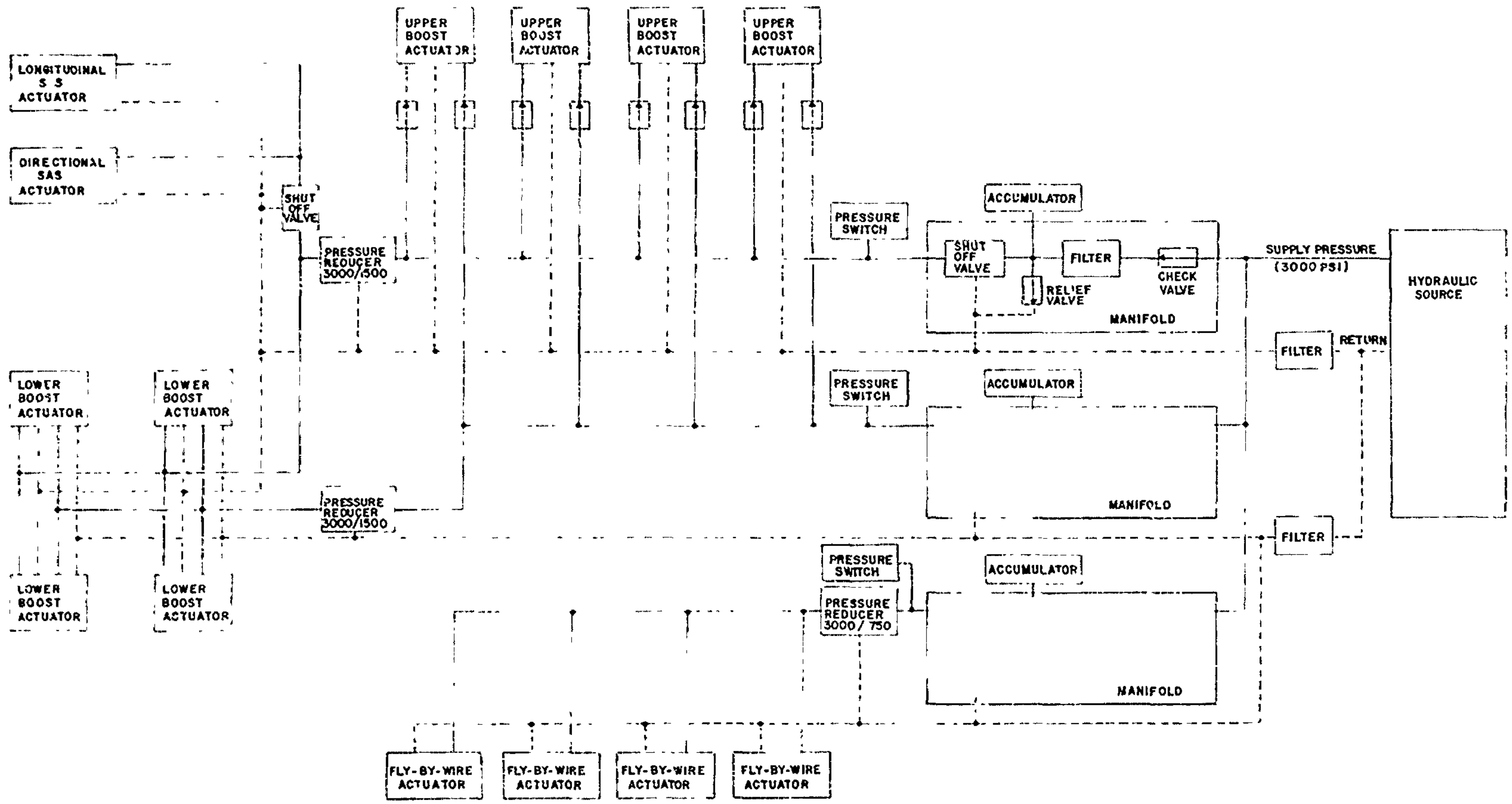


FIGURE 14. FLIGHT CONTROL SYSTEM - HYDRAULIC SCHEMATIC CH-47C FLY-BY-WIRE BACKUP DEMONSTRATION

FLY-BY-WIRE BACKUP CONTROL SYSTEM INSTALLATION ON TEST RIG

MODIFY "IRON BIRD" TEST RIG

Modifications defined in "Iron Bird" Test Rig Modification Definition section were incorporated into the Boeing test rig.

MODIFICATION AND INSTALLATION OF ONE CHANNEL OF EXISTING HLH ATC DELS

Modifications identified in ATC DELS Modification Definition section were accomplished under subcontract by the General Electric Company. General Electric data on these modifications and their test results is included in Appendix B.

FUNCTIONAL CHECKOUT OF INSTALLED SYSTEM

All functional checkouts were accomplished in accordance with the Test Outline, Appendix A. Results of these tests are summarized below.

Mechanical System

Cockpit controls were balanced by addition and deletion of weights per D347-10095-1.

System and actuators were checked for looseness and binding. The only problem found was excessive friction at the forward left upper boost input. Initial friction of ±10 lb was reduced to ±5.5 lb. Friction resulted from ingestion of dirt into valve clevis area because laboratory actuators are not fitted with protective boots.

A qualitative check of the cockpit force feel was made:

1. Two centering springs were adjusted to minimize deadzone, and adjustments were made to the magnetic brake stops. The pedal magnetic brake was moved to clear an interference.

2. Voltage suppression diodes were added across the magnetic brakes to prevent interference with the DELS failure display during switching.

Stability Augmentation System

Response to SAS test switch inputs was verified.

Response to sinusoidal inputs was measured in the longitudinal

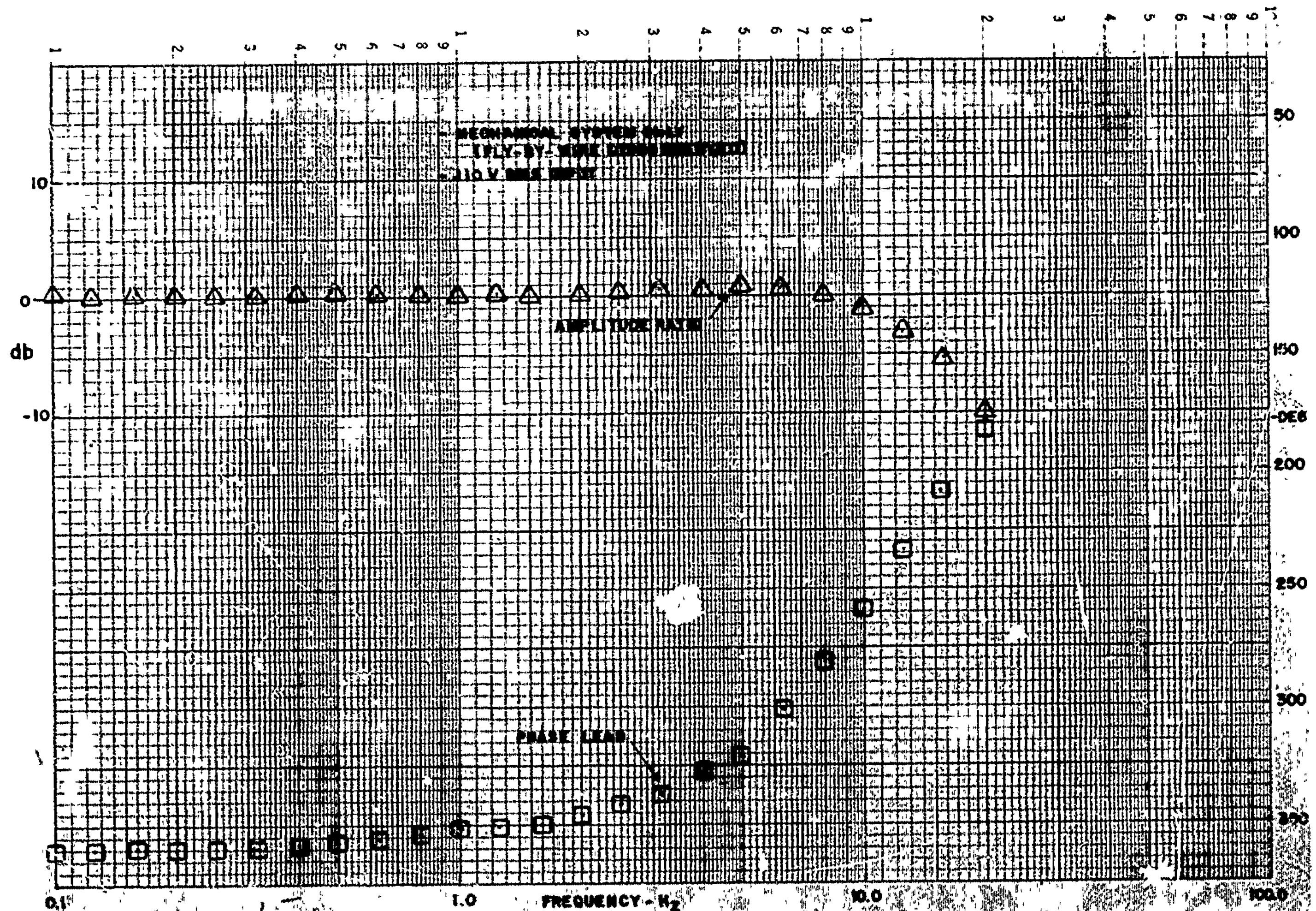


FIGURE 15. DIRECTIONAL SAS ACTUATOR VS DIRECTIONAL SAS COMMAND

and directional axes. A typical response plot for these tests is shown in Figure 15. Other plots are shown in Appendix D. Responses are in terms of FBW input buffer voltages. These responses are considered typical and serve as the baseline for comparisons with fly-by-wire response.

The interface into the FBW Control Unit was checked, and changes in phasing to assure proper polarity were made.

Hydraulic shutoff valves were checked. Diodes were added to suppress interference with failure displays.

Electrical Link Functional

FBW Checkout--Initial functional checkout of the FBW with mechanical system revealed the need to make some revisions to the force fight comparitor and differential pressure feedback switching.

Initiation of a failure causing a shutdown resulted in the differential pressure signal going to the bypass position to indicate pressure loss (Figure 16). For one polarity of failure (that which was in the same direction as the bypass indication), shutdown was normal. For the opposite polarity of failure, a cycling action occurred.

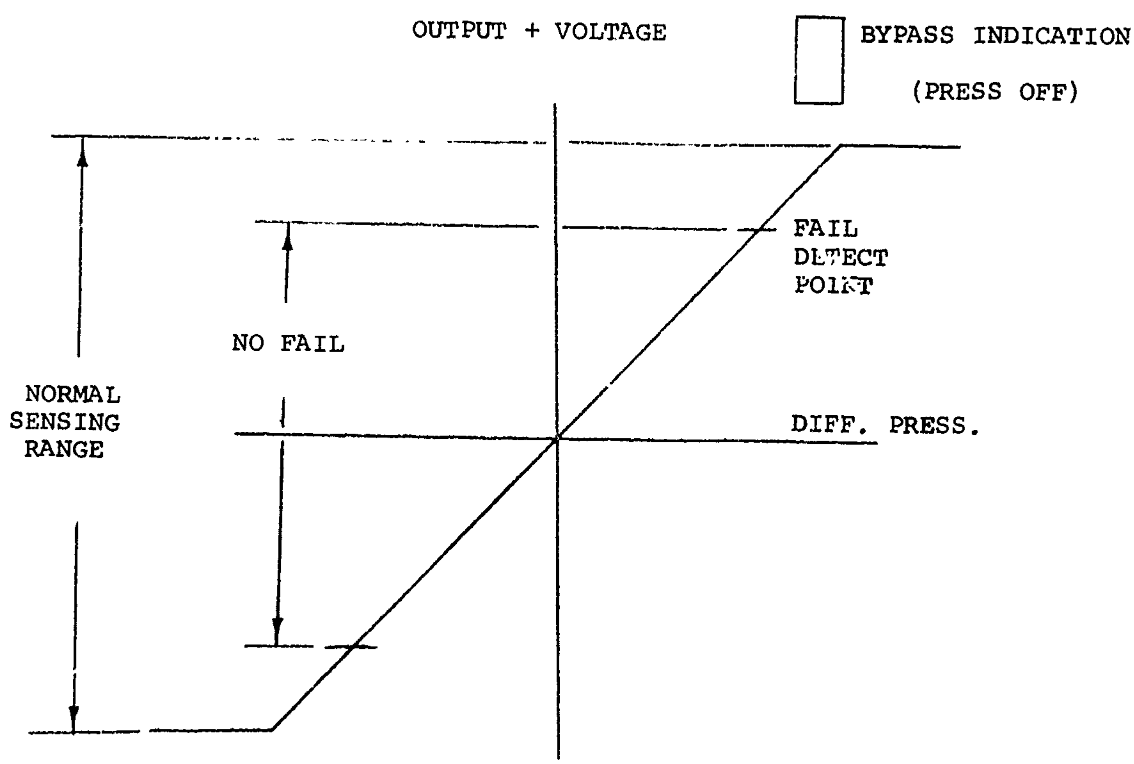


FIGURE 16. DIFFERENTIAL PRESSURE SENSOR OUTPUT

When the output drove to the negative fail detect level, shutdown of the actuator was initiated. This caused the differential pressure output to reverse and go through the NO FAIL region toward the BYPASS point (Figure 16). When the actuator entered the NO FAIL region, it reengaged and Delta P differential pressure again headed towards the negative fail detect point and the cycle repeated.

To overcome this problem, an electronic latching circuit was added to the output of the force fight detector so that once tripped, it was latched until the pressure signal went to the BYPASS point.

A second problem occurred when the actuator was reengaged after shutdown.

When the actuator is shut down there is a large differential pressure signal present because the sensor is in the bypass state. This signal acts via the differential pressure feedback to command an offset between the fly-by-wire and the mechanical system. When reset is initiated, two things happened:

1. There was an initial offset between the systems which decayed as the differential pressure feedback went to zero through the .5 sec lag in the differential pressure feedback shaping.

2. There was a spurious force fight indication generated by the initial pressure sensor offset.

These problems were overcome by switching off the differential pressure feedback until the system was fully engaged. Response to built-in test, pilot, and SAS inputs was normal.

Mechanical Stops--Adjusting the mechanical stops relative to electrical limits was found to be difficult because there were three sets of stops involved.

The mechanical mixer stops were coordinated with the electrical limits, but this was not enough to prevent mistrack because of the additional compliance between the stick position transducers, located on the right hand pilot's side, and the mechanical stops on the left hand side. Separate axis stops near the transducer had to be adjusted to coincide with the other systems stops. As discussed previously, this problem is only related to the test stand since in production the SPT would be mounted on the lower boost actuator which is in closer proximity to the stops.

Difficulties in adjusting stops lead to one decision for production. There will be no separate stops in the electrical system. That system will have range in excess of that required by the mechanical limits. Under this condition, there can be a force fight at the stops.

Failure detection will be overridden when the system is near the stops (i.e., 2/3 of full travel). This method has two benefits:

1. Eliminates need for close coordination of stops.

2. Removes the extreme travel condition, wherein the maximum mistrack and nonlinearity induced differences can occur from failure detection circuits.

There is no compromise of safety since the pilot rarely, if ever, gets to these extremes in flight for more than a few seconds.

Tracking--Tracking of the electrical and mechanical systems was checked with the swashplate driver actuators connected. Tracking of the two systems was assessed by plotting swashplate driver actuator position versus axis command for displacement over the full axis travel. Plots were made for fly-by-wire engaged, differential pressure feedback OFF, and fly-by-wire disengaged.

Significant gain errors were found in the directional axis input. Figures 17 and 18 show the comparison of axis gain before and after adjustment to reduce electrical system gain. At this time, system stops had not been fully adjusted. Note the extra travel achieved by the electrical system. This results from deflection of the control runs to allow further travel beyond the mechanical limits. Subsequent to these plots, the gain of the electrical system was further reduced and stops were adjusted to eliminate the overshoot at the stops.

HLH ATC gains were based on nominal mechanical system kinematics. Exact tracking of the systems was not critical in the fly-by-wire program because either one or the other system was controlling. Gain errors found in this program point to the need for accurate assessment and analysis of gains and allowable errors in the mechanical system so that accurate tracking and compensation of the two systems can be achieved.

Another source of error is variation of mechanical system position due to thermal expansion in the long mechanical control run. Shifts of null between the two systems have been seen on the test stand. The stand has a steel frame and aluminum control rods. This means that differential expansion will occur. Although these offsets have not been pinned down to thermal expansion, they point to the need to understand thermal effects so that they can be considered in establishing differential pressure feedback gains. In the aircraft we have an aluminum fuselage with aluminum rod, so there is better compensation for thermal effects.

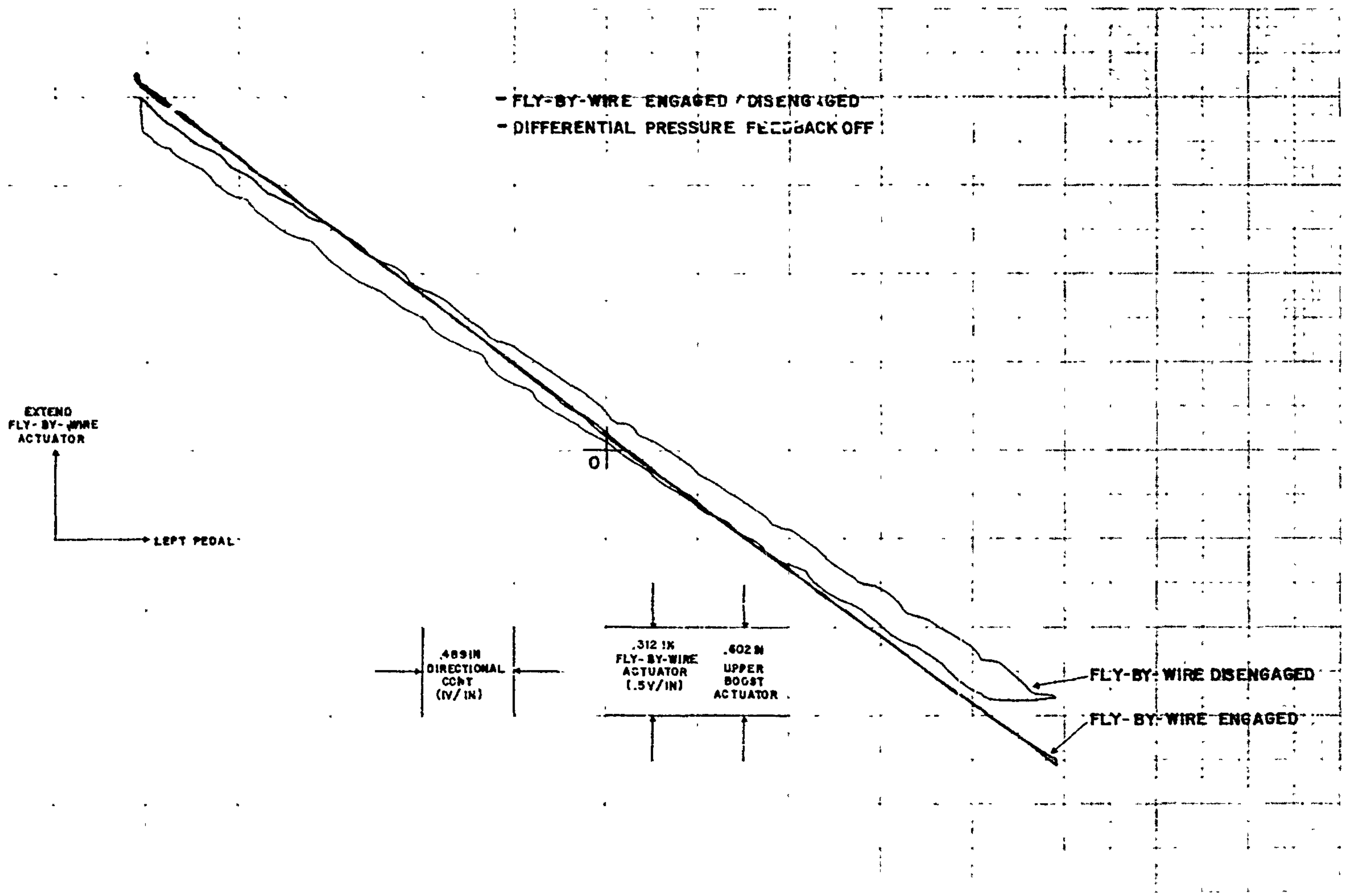


FIGURE 17. AFT LEFT FLY-BY-WIRE ACTUATOR DISPLACEMENT (TP-46) VS DIRECTIONAL AXIS DISPLACEMENT (TP-13)

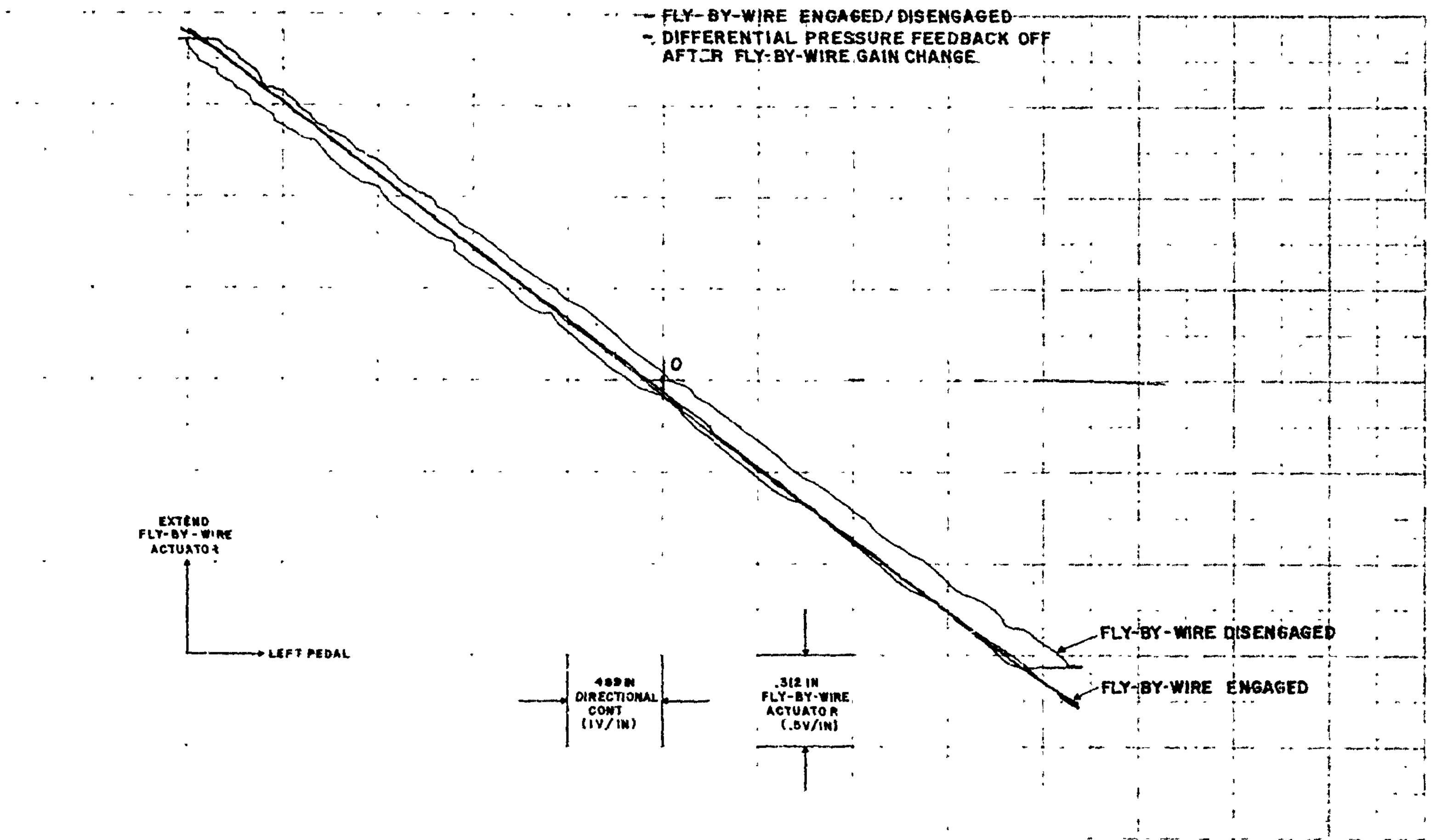


FIGURE 18. AXIS LEFT FLY-BY-WIRE ACTUATOR DISPLACEMENT (TP-46) VS DIRECTIONAL AXIS DISPLACEMENT (TP-13)

TESTING AND PERFORMANCE EVALUATION

All testing and performance evaluations were accomplished in accordance with the Test Outline, Appendix A.

MECHANICAL SYSTEM OPERATIONAL CHARACTERISTICS

Static Characteristics

Mechanical System--Static characteristics of the mechanical system were measured. Plots were made to show the performance of each upper boost actuator in response to each axis input. Sixteen plots were made. Figures 19 and 20 are typical of these. Note that the hysteresis is smaller for the small amplitude displacement. This is because the system is moving through a smaller change in friction and the preloading springs are more effective. Note that the aft left response shows slightly greater hysteresis. This is due to added compliance and function in the aft run. The preloaded mechanical system has good hysteresis characteristics. Early CH-47A aircraft without springs had several tenths of an inch hysteresis.

Fly-By-Wire--Static characteristics of the fly-by-wire channel were measured with and without differential pressure feedback on. These tests were made with the actuators disconnected. Figure 21 shows response for the forward right actuator. Note that with differential pressure feedback OFF, there is no measurable hysteresis in the response, while with differential pressure feedback ON, the hysteresis similar to that measured for the mechanical system is present. The value of gain used in this plot is that used for the HLH ATC Program. The final value selected for this program was one-third the gain of the HLH, so that the expected hysteresis is approximately one-third that shown in Figure 20.

Figure 22 shows the response of the aft left actuator for differential pressure feedback OFF. It is similar to Figure 21.

Dynamic Characteristics

Mechanical System--Dynamic characteristics of the mechanical system were measured by making sinusoidal inputs to the longitudinal and directional SAS actuators. Magnitudes selected represent approximately 10 percent and 20 percent of single SAS authority.

The response to the larger input is shown in Figures 23 through 26. The response for the smaller input will be shown later, superimposed with the data taken with fly-by-wire on.

The result shows good response for both axes; the phase shift at low frequency is 10-15 degrees, and the

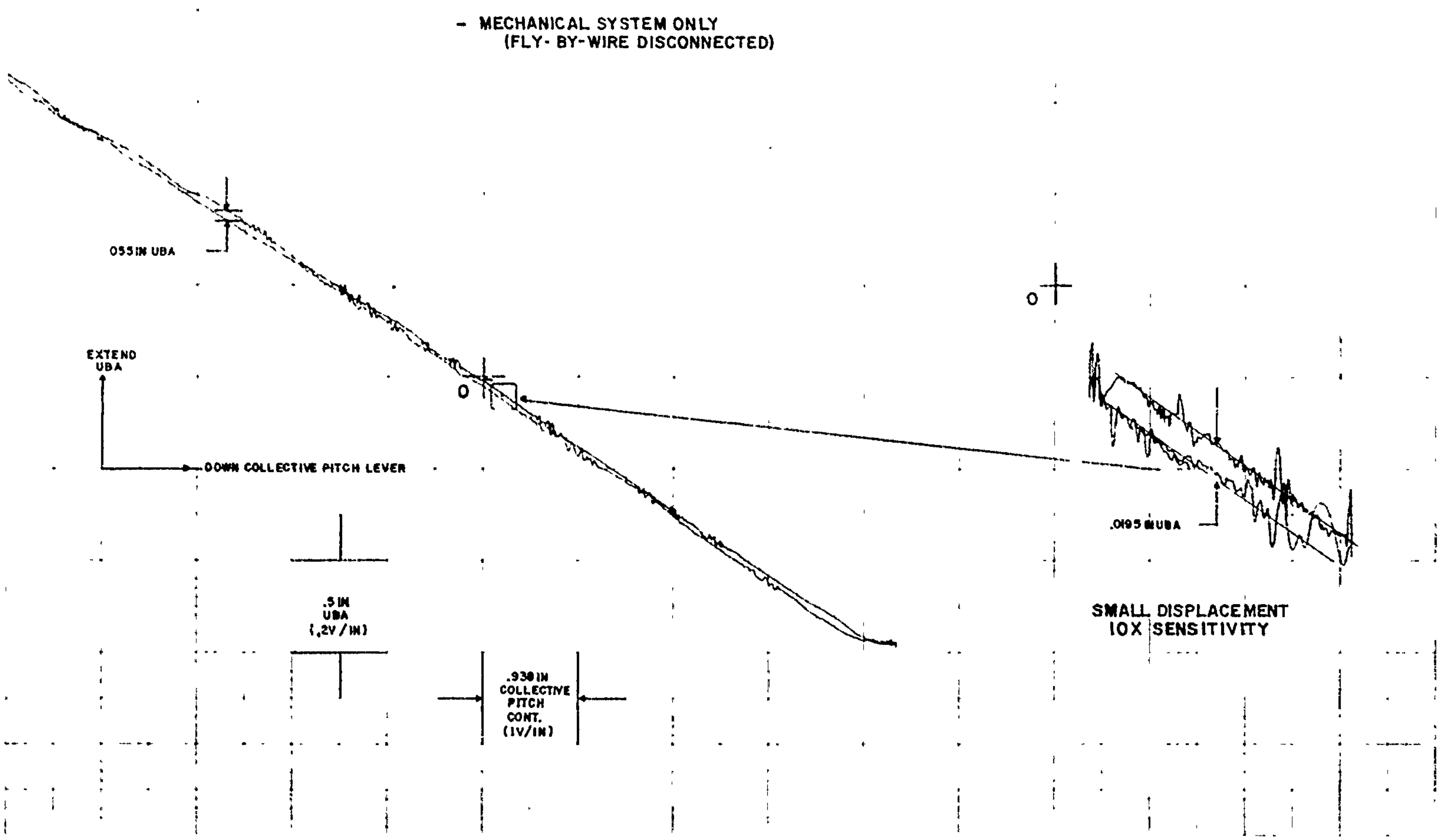


FIGURE 19. FORWARD RIGHT UPPER BOOST ACTUATOR VS COLLECTIVE PITCH AXIS DISPLACEMENT (TP-15)

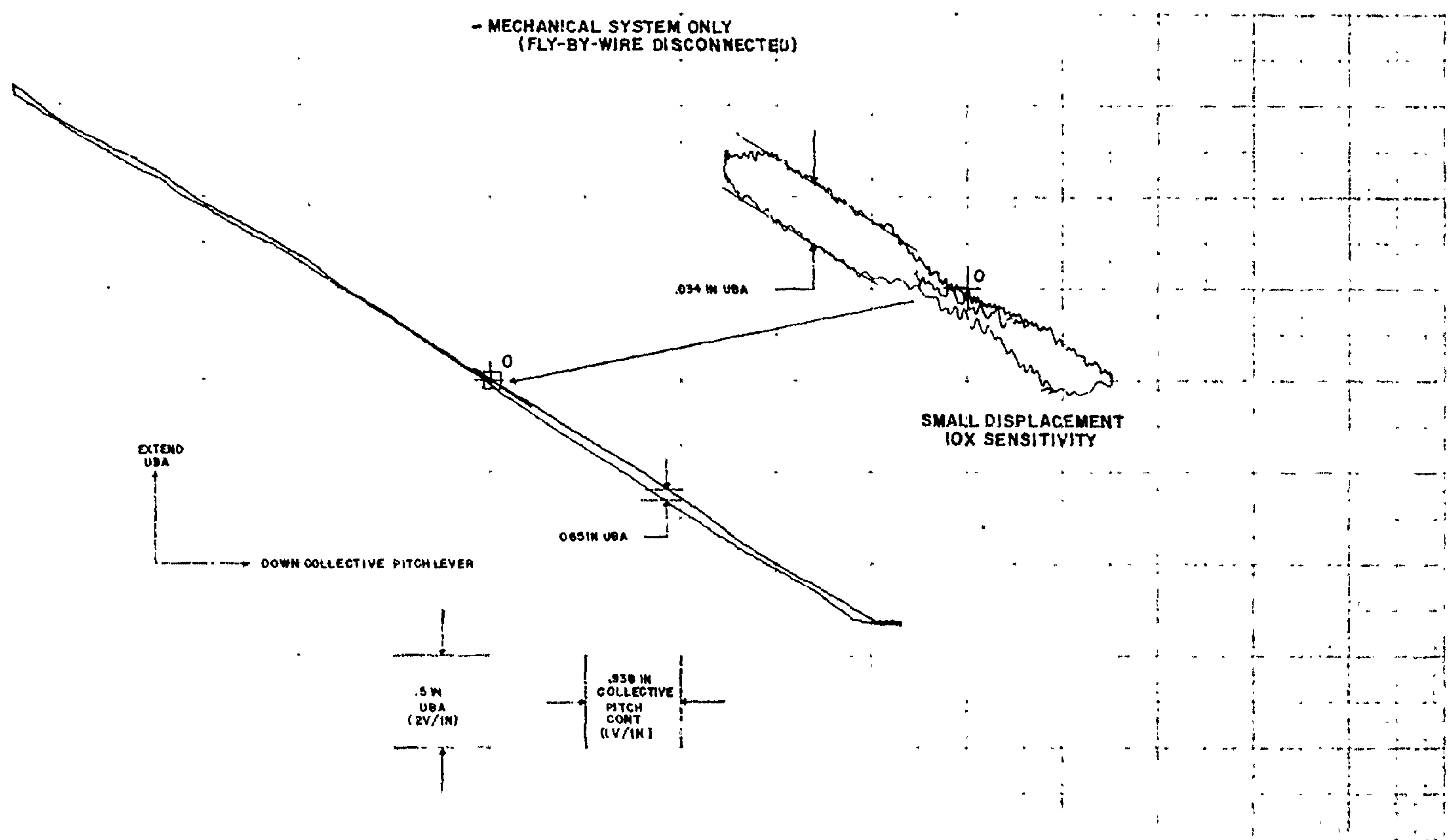


FIGURE 20. AFT LEFT UPPER BOOST ACTUATOR VS COLLECTIVE PITCH AXIS DISPLACEMENT (TP-15)

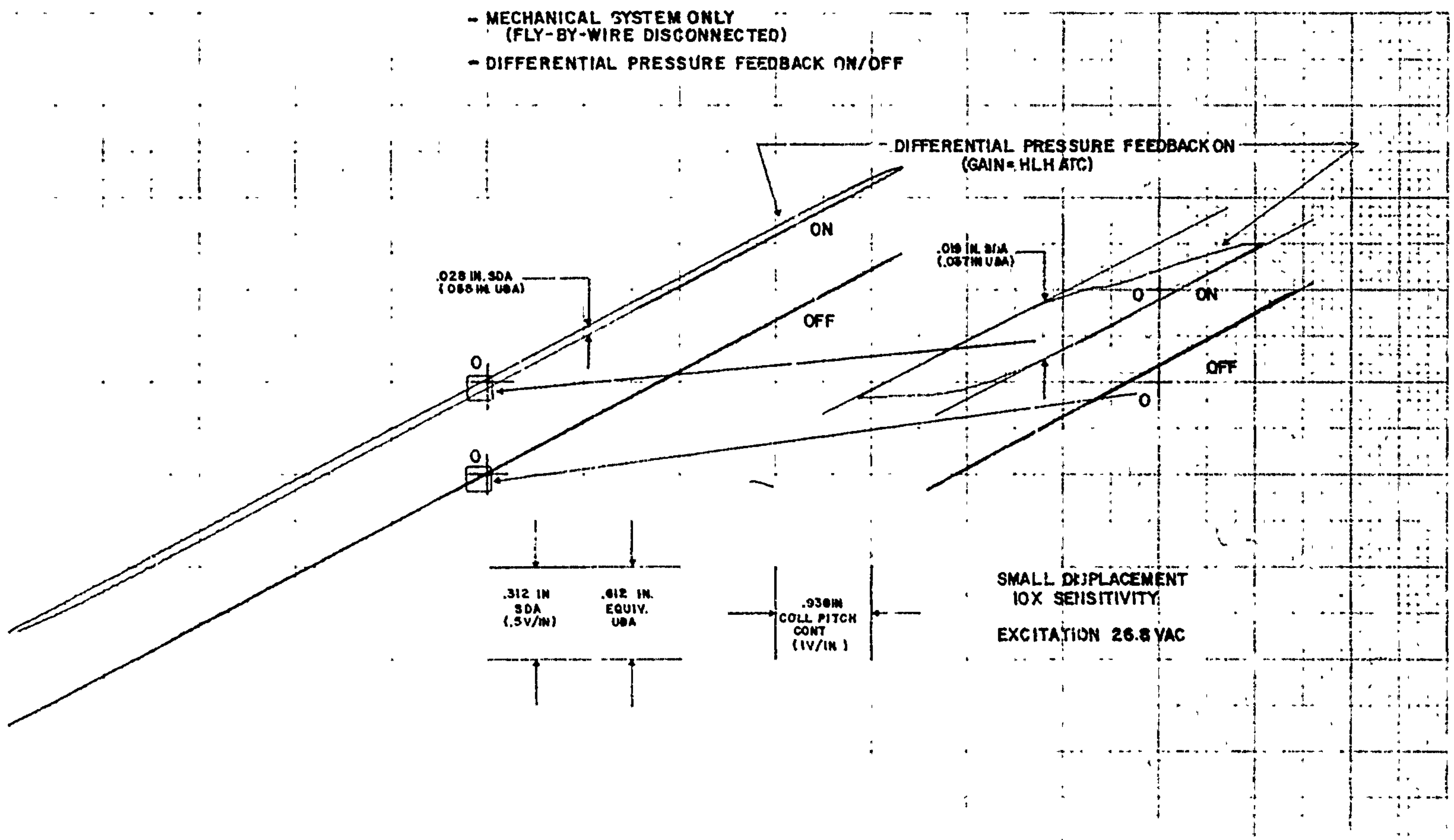


FIGURE 21. FORWARD RIGHT FLY-BY-WIRE ACTUATOR (TP-34) VS COLLECTIVE PITCH AXIS DISPLACEMENT (TP-15)

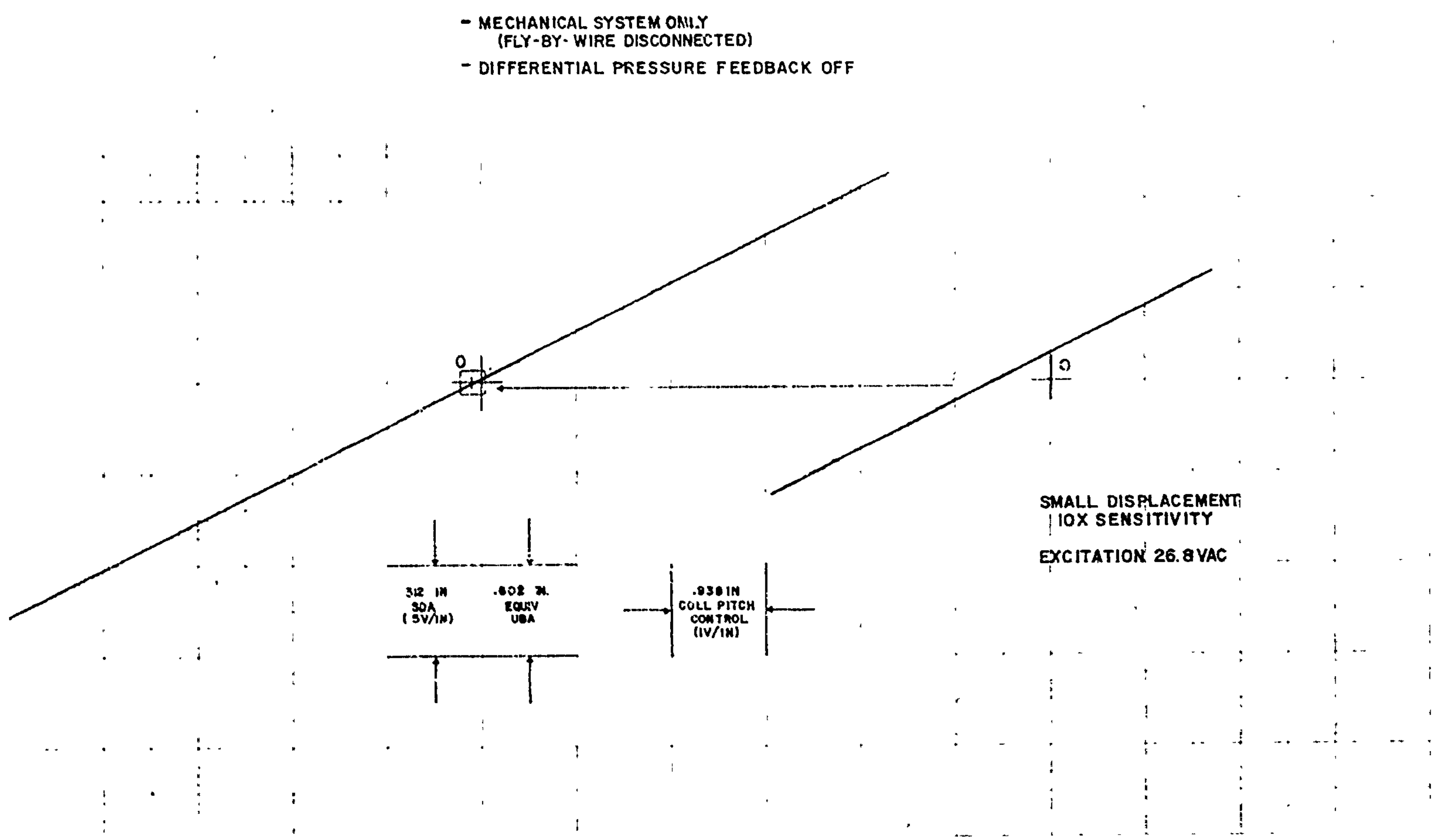


FIGURE 22. AFT LEFT FLY-BY-WIRE ACTUATOR (TP-34) VS COLLECTIVE PITCH AXIS DISPLACEMENT (TP-15)

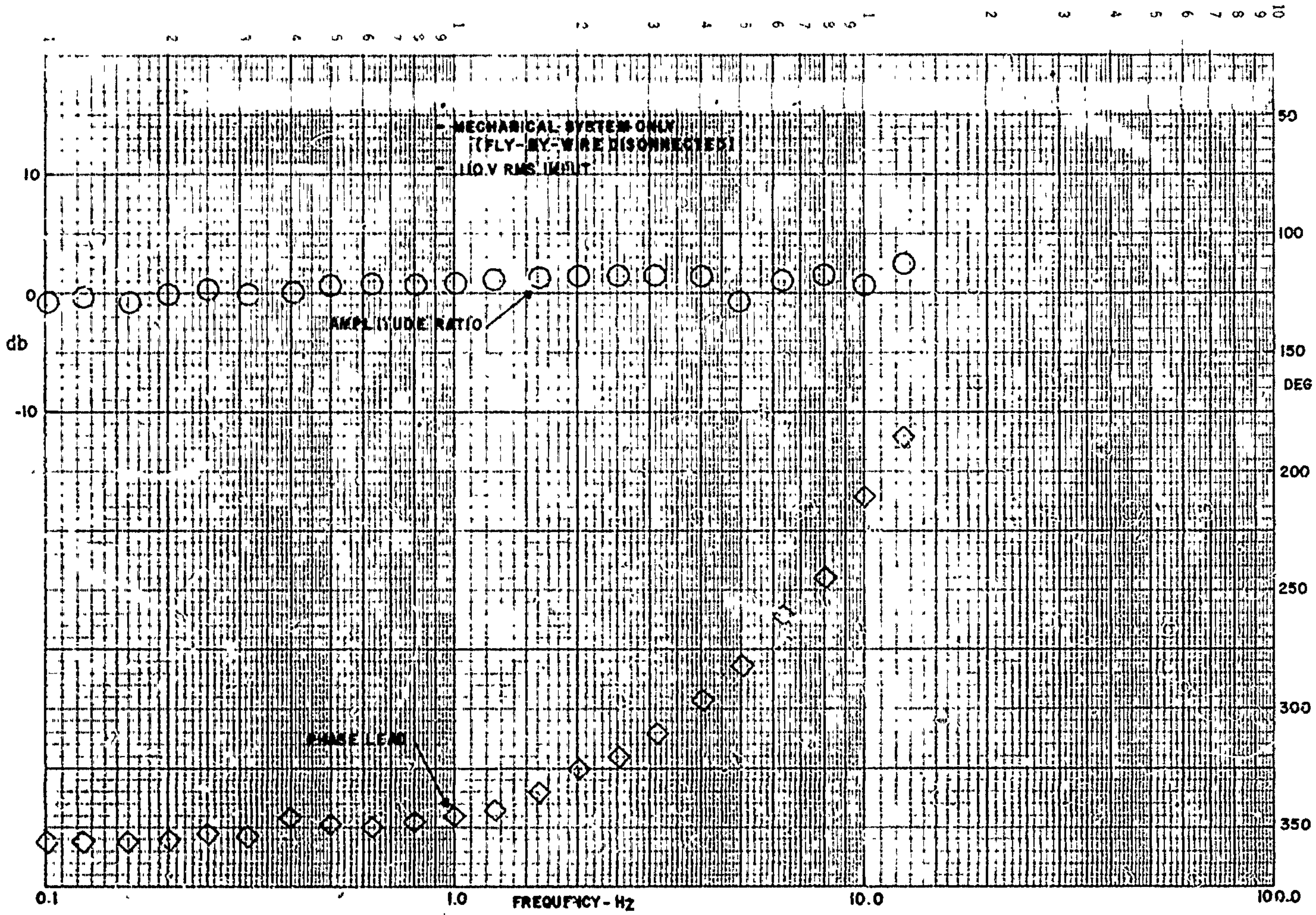


FIGURE 23. FORWARD RIGHT UPPER BOOST ACTUATOR VS LONGITUDINAL SAS COMMAND

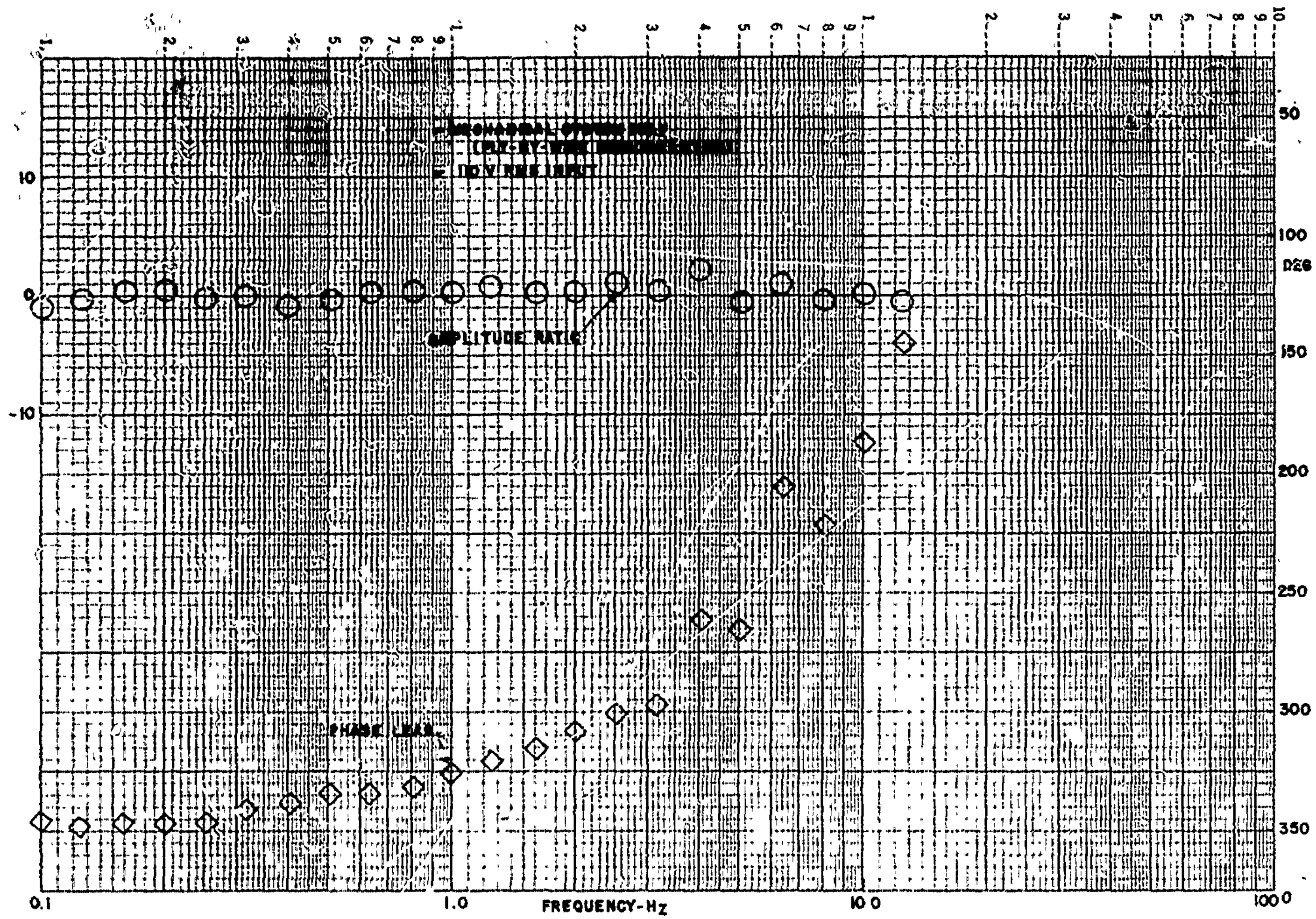


FIGURE 24. AFT LEFT UPPER BOOST ACTUATOR VS LONGITUDINAL SAS COMMAND

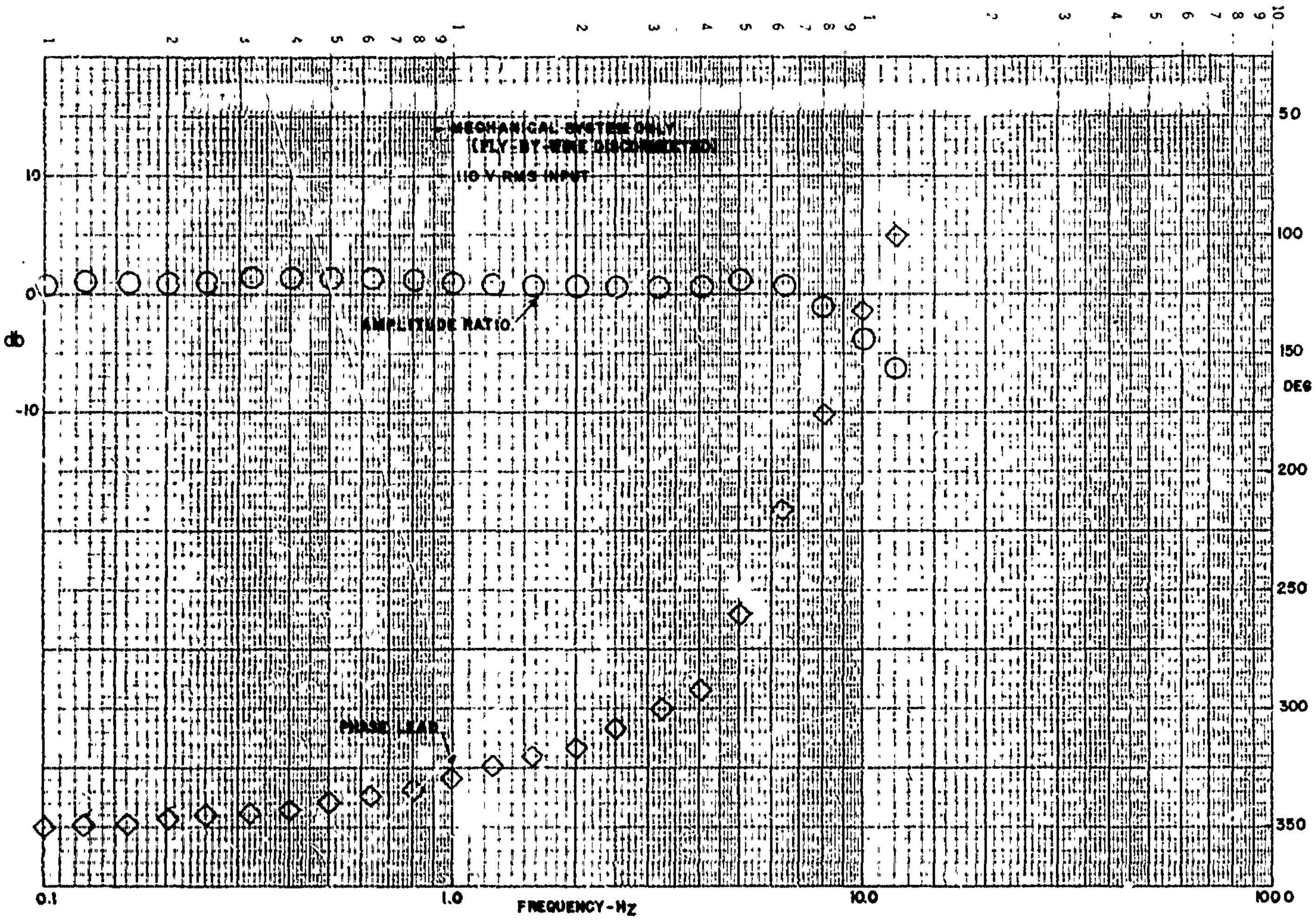


FIGURE 25. FORWARD RIGHT UPPER BOOST ACTUATOR VS DIRECTIONAL SAS COMMAND

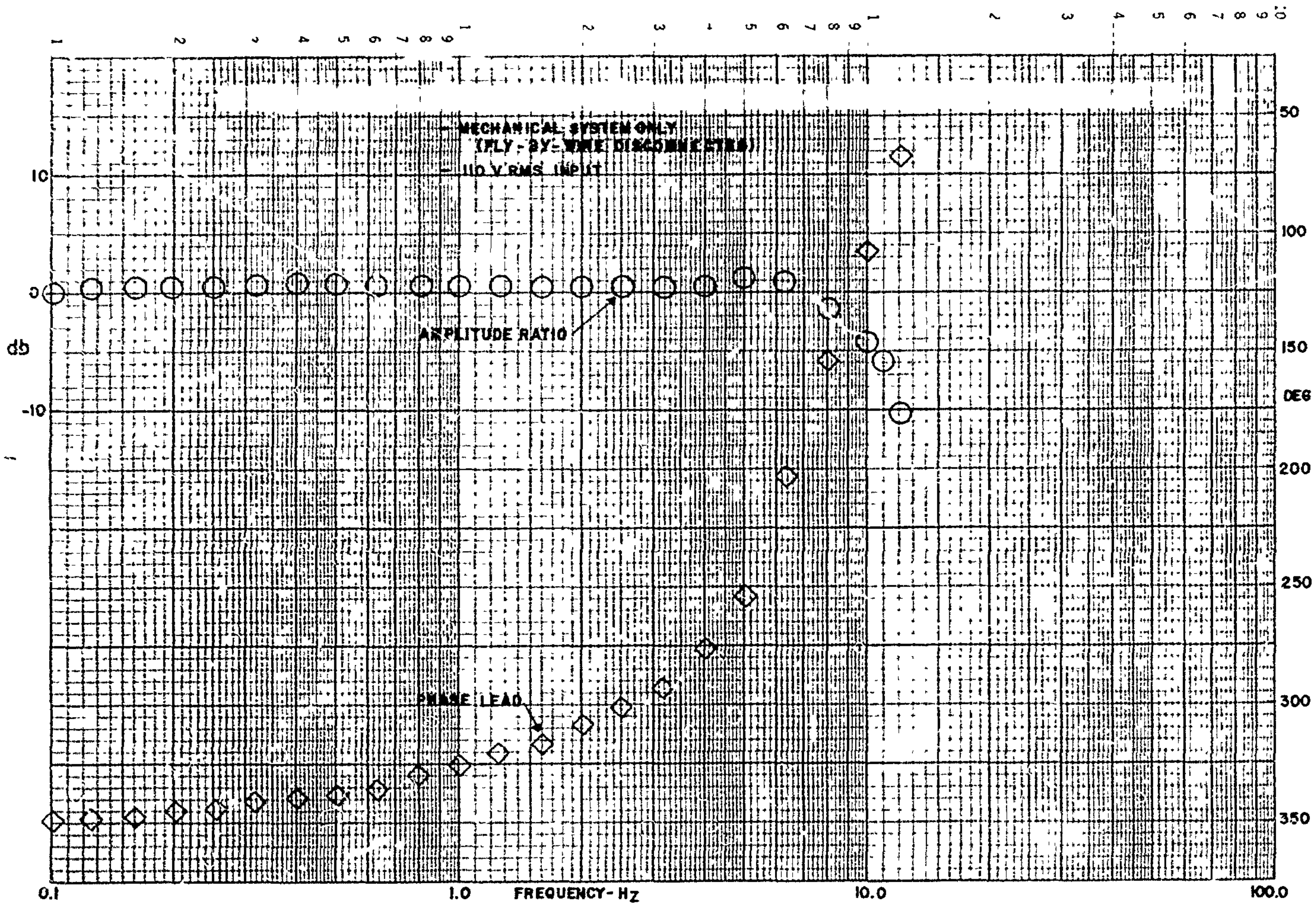


FIGURE 26. AFT LEFT UPPER BOOST ACTUATOR VS DIRECTIONAL SAS COMMAND

amplitude response is flat within ±3 db out to approximately 10 Hz.

Since SAS stabilizing signals are in the order of .5 to 1.0, the response is considered to be very good.

Fly-By-Wire--Unloaded fly-by-wire actuator response was measured to provide a baseline. Figure 27 shows response of the forward right actuator with differential pressure feedback OFF. The response is good. Low frequency phase shift is less than 10 degrees. The actuator accurately tracks the response of the SAS actuator as shown in Figure 15. Deviation in response occurs only at the higher frequencies.

Other mechanical system baseline data may be found in Appendix D.

PERFORMANCE CHARACTERISTICS WITH FBW CONNECTED

Differential Pressure Feedback OFF

Static Characteristics--Static characteristics similar to those conducted for the baseline tests were operated with differential pressure feedback OFF. Figures 28 and 29 show response for collective pitch axis inputs. These are for similar conditions as shown in baseline data Figures 19 and 20. Note the improvement in hysteresis, in particular, at the low amplitude input. These data show the benefits to be derived from use of a stiff fly-by-wire channel working against the mechanical system compliance.

Differential Pressure Tracking--Figure 30 shows a time history of actuator position and pressure response with no differential pressure feedback. The force fight comparitor is set to trip at ± 80 lb (±2.8 VDC). Note that the variation in pressure approaches this limit. This variation shows the need to soften the actuator output stiffness using differential pressure feedback.

Dynamic Characteristics--Dynamic response with no differential pressure feedback is shown in Figure 31, along with response with two of the differential gain valves studied. Note that the differential pressure feedback OFF plots show the best phase response at low frequency. It is better than that achieved by the mechanical system.

Differential Pressure Feedback ON

Static Characteristics with Error--To assess the capability of differential pressure feedback to allow greater error between systems, plots such as Figure 32 were made.

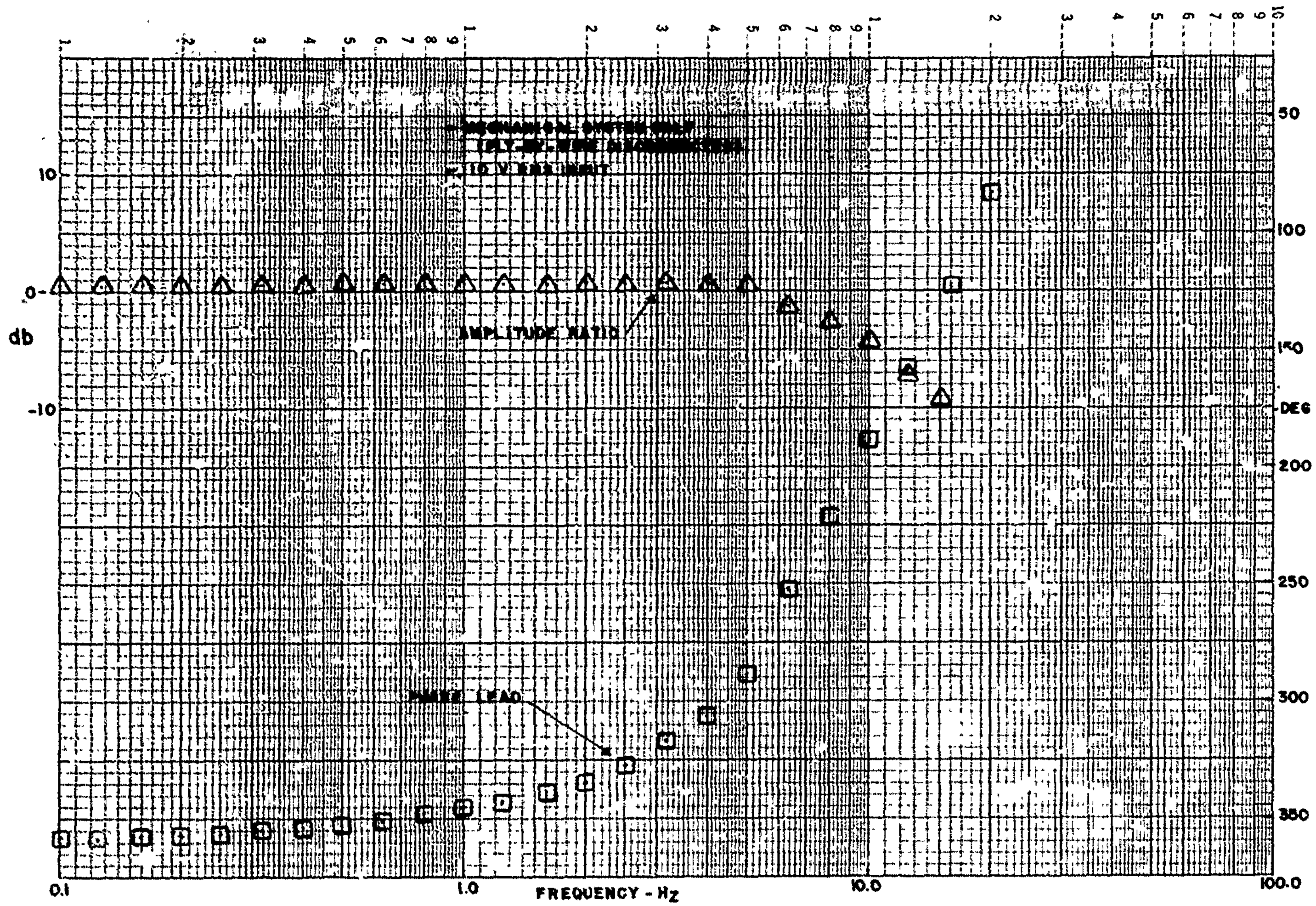


FIGURE 27. FORWARD RIGHT FLY-BY-WIRE ACTUATOR VS DIRECTIONAL SAS COMMAND

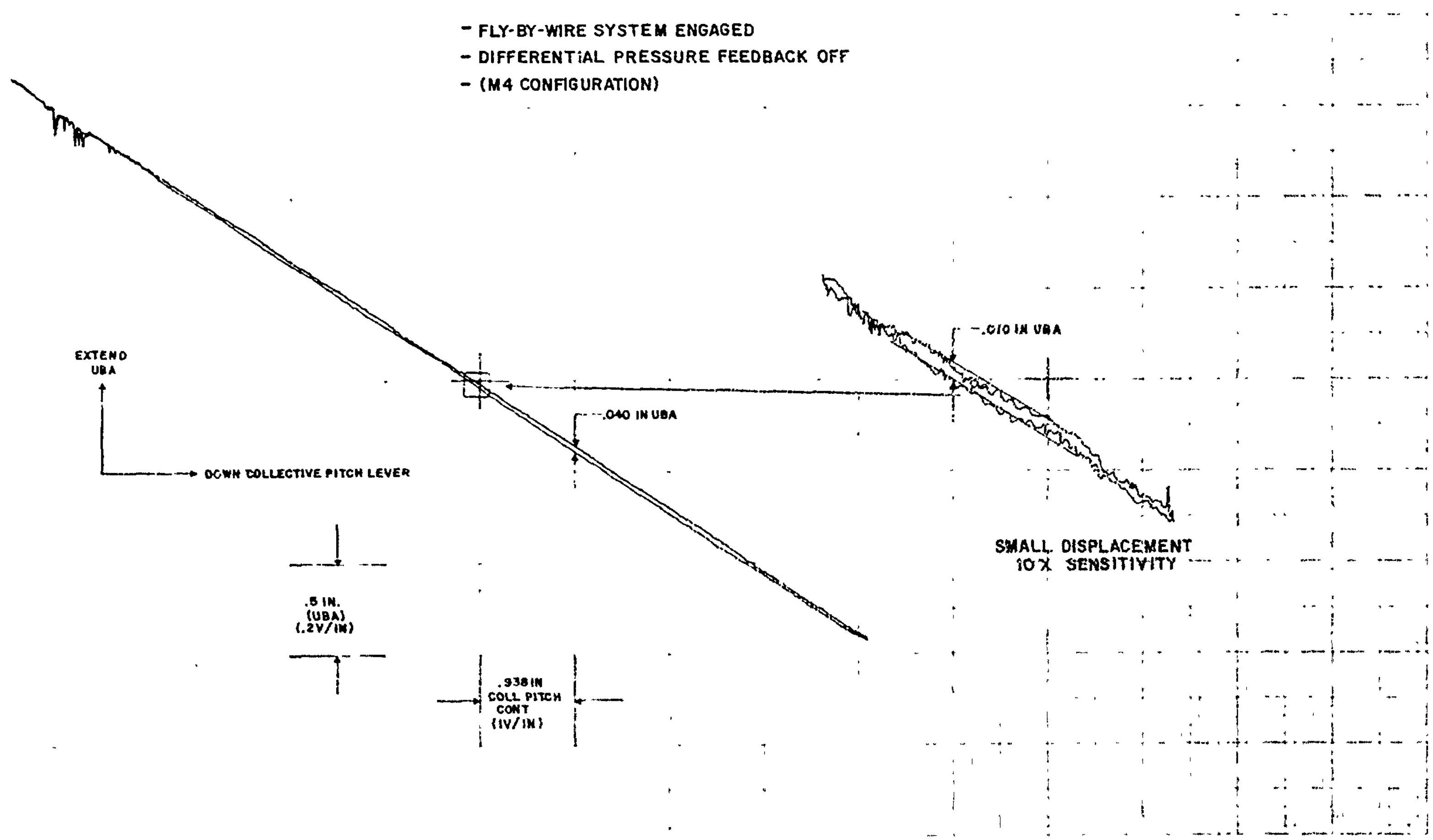


FIGURE 28. FORWARD RIGHT UPPER BOOST ACTUATOR VS COLLECTIVE PITCH AXIS DISPLACEMENT (TP 15)

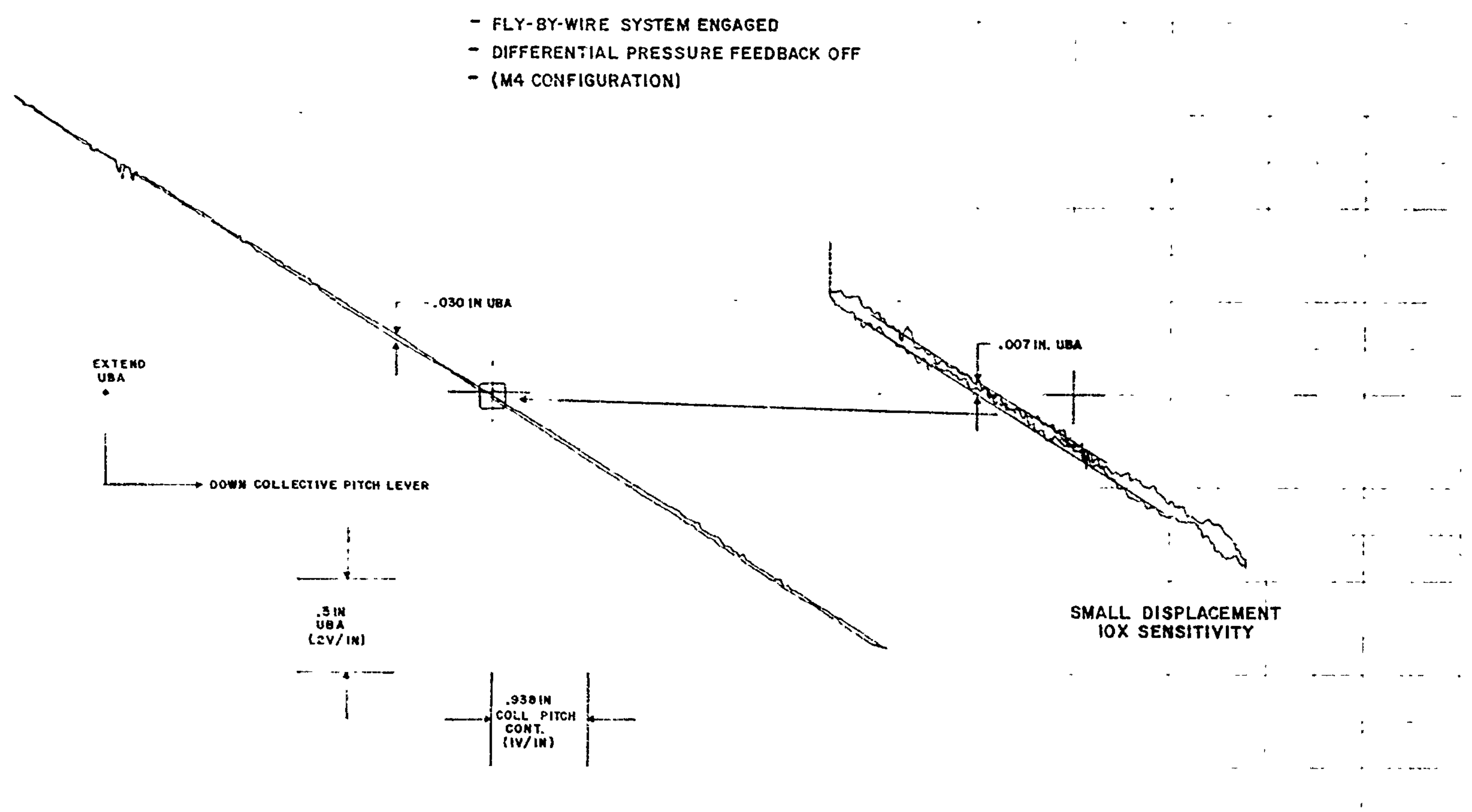


FIGURE 29. AFT LEFT UPPER BOOST ACTUATOR VS COLLECTIVE PITCH AXIS DISPLACEMENT (TP-15)

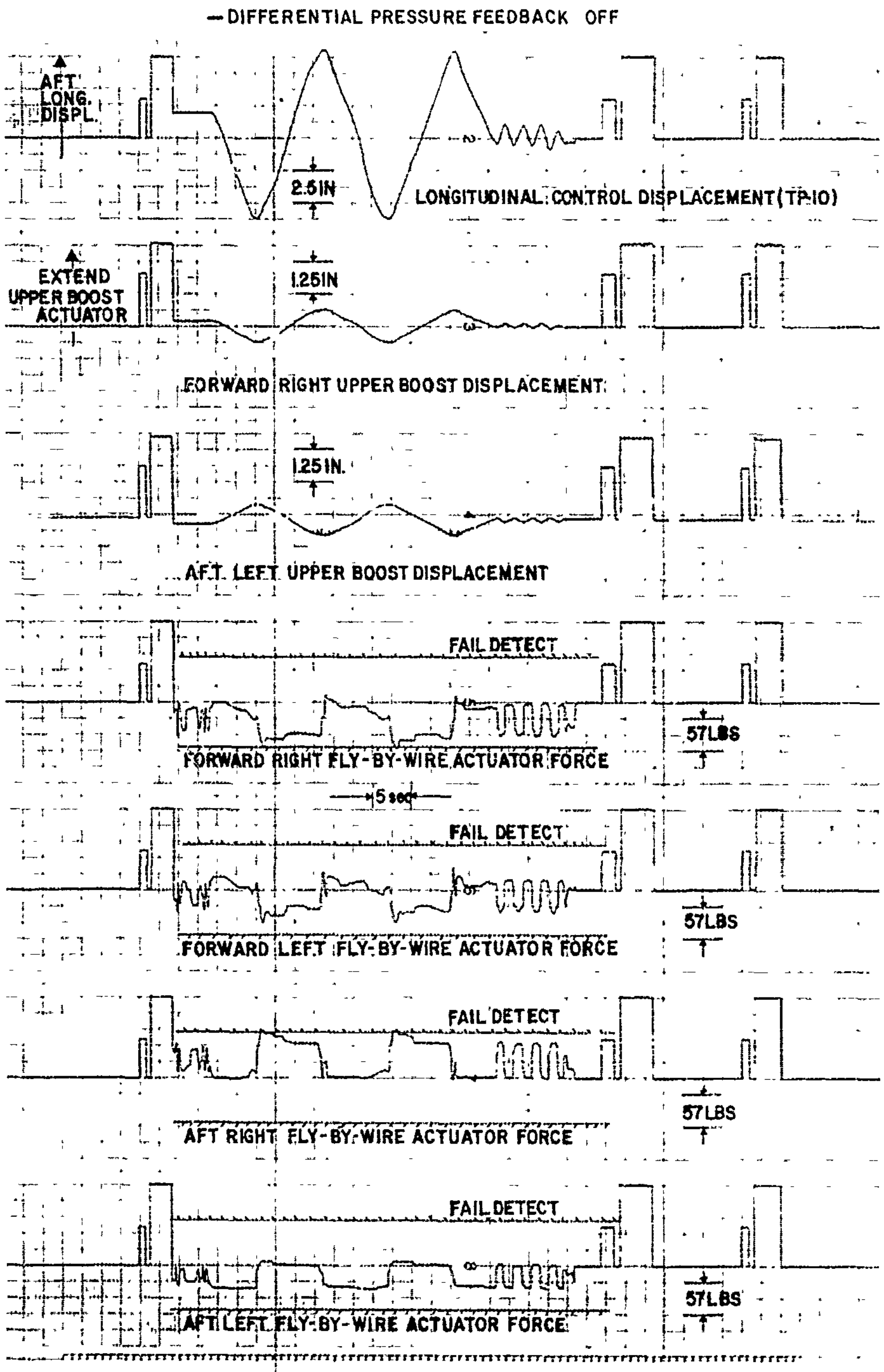


FIGURE 30. TIME HISTORY-UPPER BOOST POSITION, FLY-BY-WIRE ACTUATOR DIFFERENTIAL PRESSURE, LONGITUDINAL CONTROL DISPLACEMENT

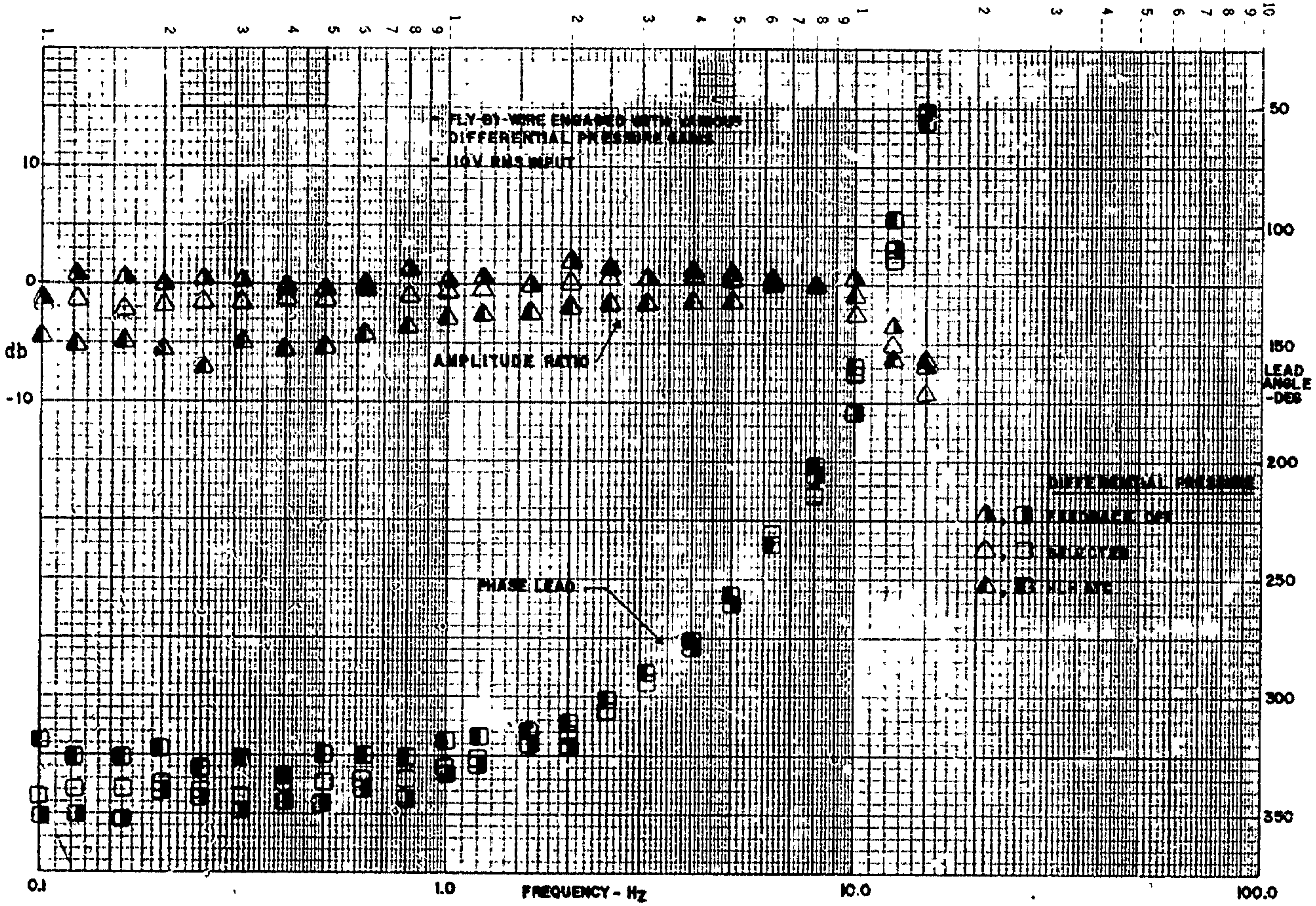


FIGURE 31. AFT LEFT UPPER BOOST ACTUATOR VS LONGITUDINAL SAS COMMAND

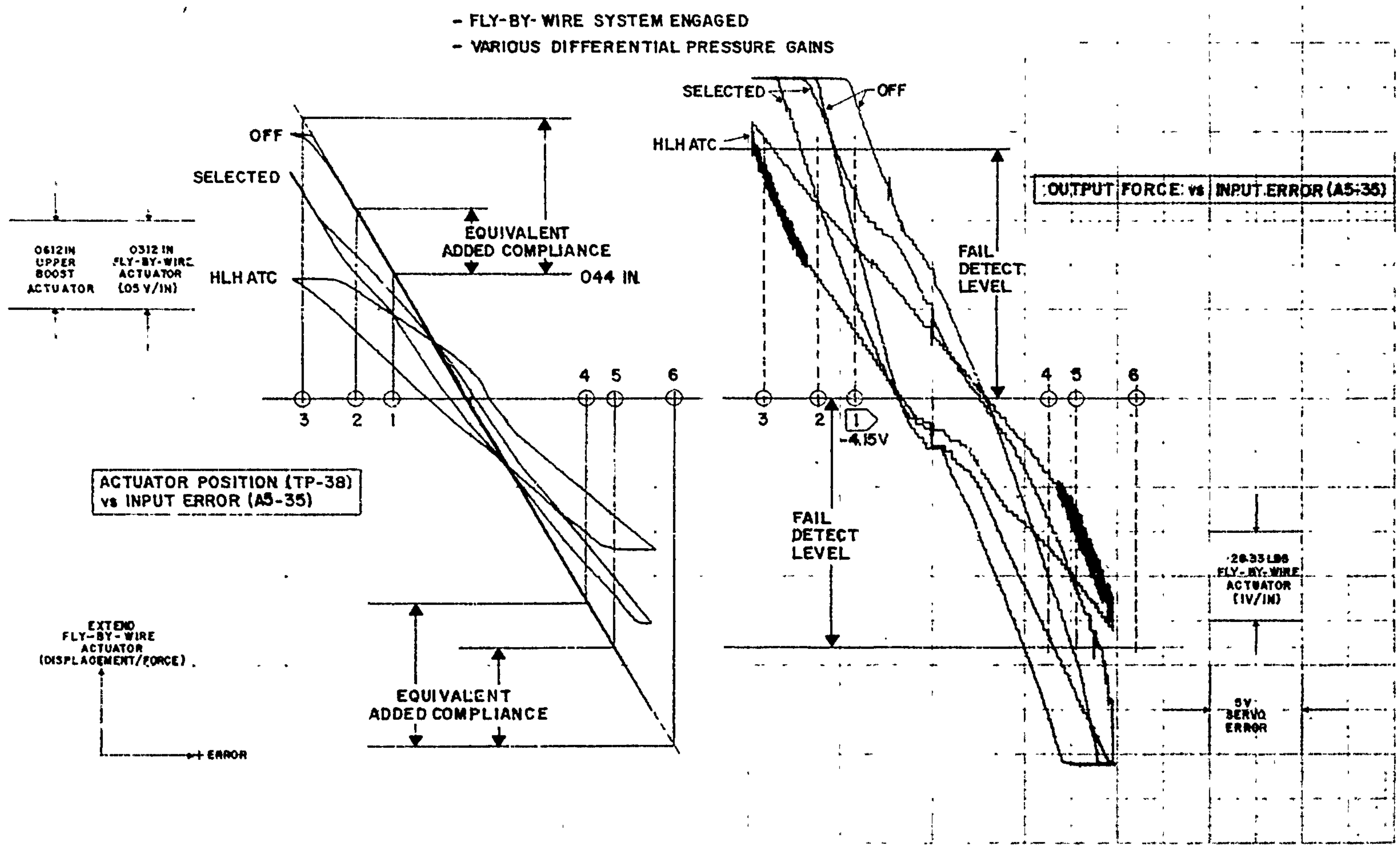


FIGURE 32. FORWARD LEFT FLY-BY-WIRE ACTUATOR VS INPUT ERROR

The plot shows the response in fly-by-wire actuator output differential pressure and ram displacement to errors introduced at the actuator servo input.

These plots were made for no differential pressure feedback and for the two other gains considered.

Note that differential pressure builds up faster with no differential pressure feedback. The failure detect differential pressure is set at 80 lb or 2.8 VDC.

Note that for this example plot, it takes -4.15 volts of error to reach the trip point without differential pressure feedback (Data Point 1). If we transfer this error to the second plot (Actuator Position versus input error), we find that the FBW actuator has deflected .044 in. That is, an error equivalent to .044 in. will trip the detector. This is a measure of the spring rate of the mechanical system.

The increased error allowed by differential pressure feedback may be determined graphically by projecting the input error necessary to produce the trip pressure onto the no differential pressure actuator displacement curve. The difference in actuator displacement is the increased error allowed by differential pressure feedback. This is illustrated by data points 2, 3, 5 and 6 on the curve.

Another way of assessing the effect of differential pressure feedback is to calculate the equivalent stiffness of the actuator as a function of differential pressure feedback gain. The calculated and measured actuator stiffness compares favorably.

The final step is to see how the capability to absorb errors compares with the predicted errors. This is discussed later after data substantiating the static and dynamic response with the selected gain and performance with various failures has been discussed.

<u>Dynamic Response with Varying Differential Pressure Feedback</u>--Dynamic response tests were used to select the differential pressure feedback gain for the recommended approach. Inputs to the longitudinal axis SAS were selected as the primary criteria because these resulted in the small relative inputs to the upper boost actuator.

The selected inputs of ±10 percent and ±20 percent single longitudinal axis authority represent ±.0188 in. and ±.0376 in. equivalent upper boost commands, respectively. If dynamic

response is good at these amplitudes, there will be no problem with other axes.

Figure 31 shows the dynamic response of the aft upper boost actuator for variable differential pressure inputs including no differential pressure feedback. The HLH ATC gain is the highest gain studied. Note the additional phase shift and attenuation at low frequency. The differential pressure feedback acts through a lag filter with a .5-second time constant so that its effect is reduced at higher frequencies. Note that, the selected gain plot gives slightly more phase shift at low frequency than the Delta P F/B off case. This amount of phase shift and attenuation is deemed to be acceptable and gives results which are comparable with the performance of the mechanical system by itself.

Another gain (lower gain) closer to no Delta P feedback was evaluated but discarded because the tendency to force fight was higher than desired.

Static Performance for the Selected Differential Pressure Feedback Gain--Figures 33 and 34 show typical static performance for the selected differential pressure feedback gain.

Note that performance achieved is essentially similar to that shown in the baseline data, Figures 19 and 20. Data for other axes is shown in Appendix E.

FAILURE PERFORMANCE EVALUATION

Hardover Failures

Hardover failures of the fly-by-wire actuator were assessed for their effect in producing a transient upset and additional effects on static performance if they were not switched out.

Transient Effects--The aircraft disturbances for each type of hardover transient are shown in Table 1. The disturbance is related to equivalent pilot control motion. If these motions are within the SAS capability to compensate, the resulting aircraft response, in the 3-second time delay required before pilot action, will be small; if the disturbance exceeds the SAS capability, it will require a system capable of removing the failure rapidly or a deviation to the Military Specification.

Actuator failures produce multi-axes disturbances in the airframe; but because of its low gain, the predominant effect is in the longitudinal axis. Axis failures are converted to equivalent axis by dividing the failure amplitude by four (since the input is to only one out of four upper boosts) and then

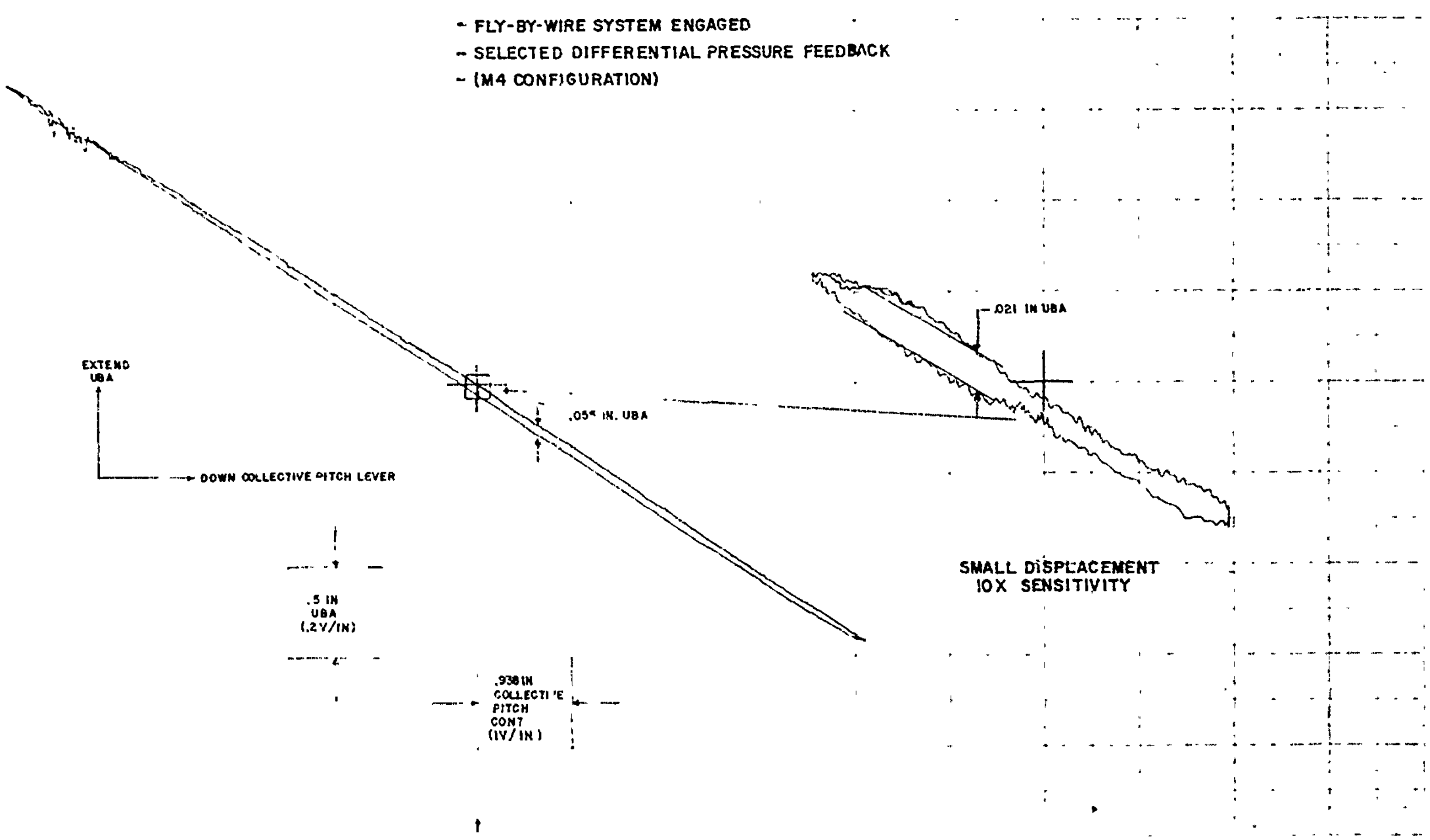


FIGURE 33. FORWARD RIGHT UPPER BOOST ACTUATOR VS COLLECTIVE PITCH AXIS DISPLACEMENT (TP-15)

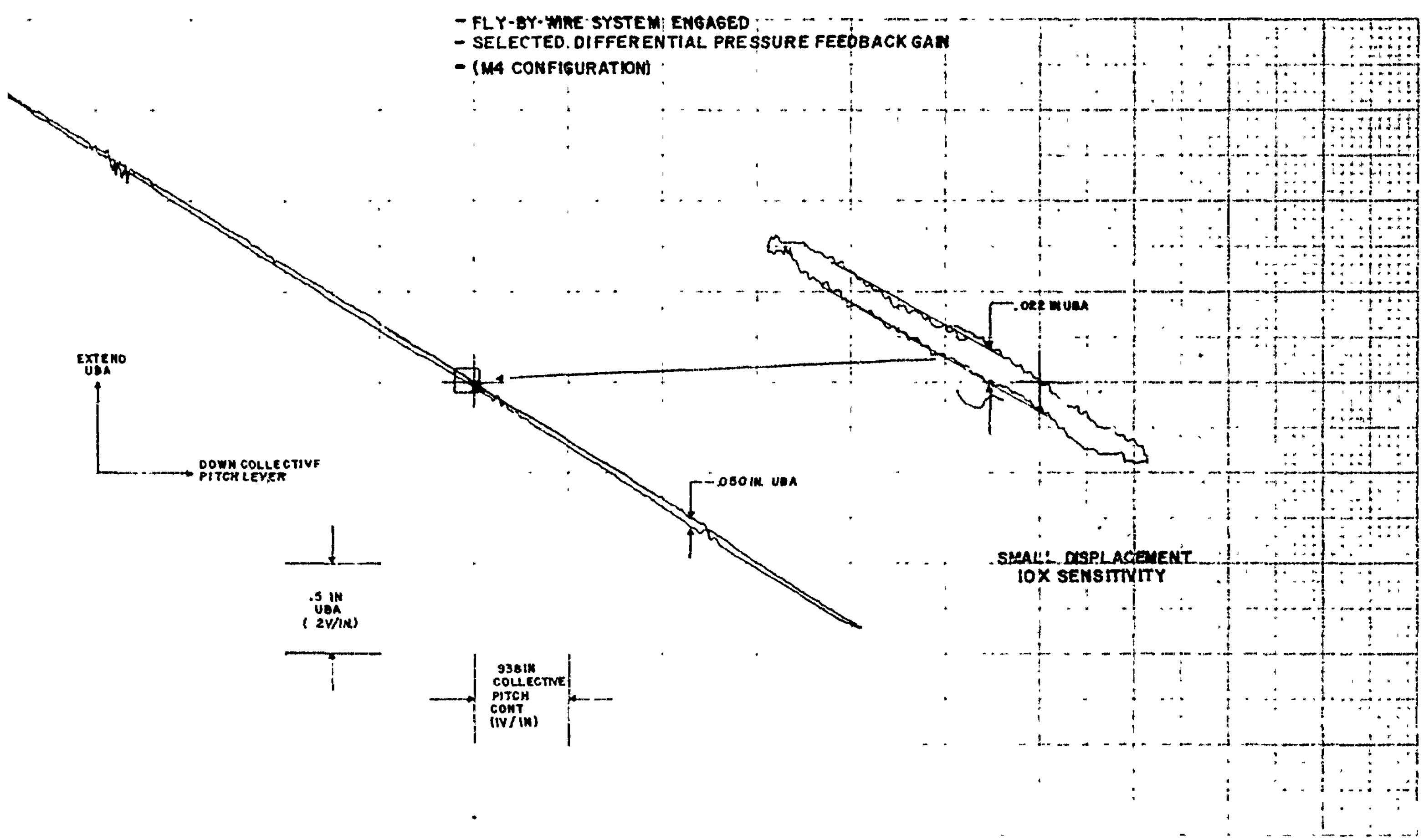


FIGURE 34. AFT LEFT UPPER BOOST ACTUATOR VS COLLECTIVE PITCH AXIS DISPLACEMENT (TP-15)

TABLE 1. MEASURED HARDOVER TRANSIENTS RELATED TO CH-47C CONTROL DISPLACEMENTS AND EXPECTED FAILURE TIME DELAY.

FAILURE TYPE	FAILURE AMPLITUDE (IN. EQUIV. CONTROL)		AVERAGE INPUT IN.	EXPECTED TIME DELAY (SECONDS)		CRITICAL PARAMETER
	UP/RT	DN/LT		DUAL SAS ON	SINGLE SAS ON	
LONGITUDINAL AXIS (PULSE LESS .25-SEC)	.75	1.65	1.20	3	3	
LATERAL AXIS[1]	.68	.62	.65	3	(>6-SEC)	ROLL ATTITUDE
DIRECTIONAL AXIS[1, 2]	.41	.37	.39	3	(>5-SEC)	ROLL RATE BUILD UP
COLLECTIVE PITCH[1]	.79	.54	.66	4	4	DOWN COLLECTIVE CLOSE TO GROUND
WORST CASE ACTUATOR[1] (EQUIVALENT LONGITUDINAL AXIS DISPLACEMENT)	.56	.84	.70	3	3 MID SPEEDS 1.5-SEC IF PSA HARDOVER	FWD. INPUT AT V_{max}. AFT INPUT NEAR HOVER

NOTES:

1. THREE-FOUR SECOND PULSE.
2. DIRECTIONAL DISPLACEMENT RATIOED FROM LATERAL DISPLACEMENT.
3. NO PILOT ACTION REQUIRED.
4. NO PILOT ACTION REQUIRED IF IN FWD. FLIGHT.
   PILOT ACTION WITHIN 3-5 SECONDS REQUIRED IF AIRCRAFT IS NEAR THE GROUND AND HARDOVER IS IN DOWN DIRECTION.

converting back to equivalent axis displacements.

The only hardover failure considered critical relative to SAS authority limits is that of the longitudinal axis. The amplitude approaches dual SAS authority and the time delay will not meet Military Specification limits. As stated previously, it is recommended that the longitudinal input be dualized so that failures may be detected without need to produce the deflection between the mechanical and electrical systems necessary to trip the force fight detector. The table shows performance with dualized input.

Other hardover failures are within the capability of the SAS to arrest within the required time delay. (Table 1)

Steady-State Effects--Static plots of the system response were made to assess the effects on hysteresis that might occur if the failure was not switched out.

Figure 35 shows the effect of collective pitch axis hardover on the collective pitch input to the aft left actuator. Normal performance and an extend and retract hardover are shown. Note that the displacment is primarily in the up direction. This is because there was an initial force unbalance in the system favoring that direction. Note that the hysteresis has increased by a factor of five from 0.04 in. to 0.195 in. This magnitude of increase in hysteresis would not significantly degrade performance except in the longitudinal axis.

Passive Failures

A second type of failure assessed was the system response to passive or "go dead" failures in the fly-by-wire channel. In this failure the fly-by-wire wants to stay at zero and the mechanical system must overpower it.

Figure 35 shows the effects on collective pitch axis. Note the distortion in response through the center of the curve. Figure 36 shows the effect of an actuator failure on the directional axis input to the aft left actuator. The nonlinear response is similar to that seen in Figure 35.

Figure 37 shows a time history response for collective pitch inputs and corresponding actuator motion. Note the attenuation of response for the passive failure (in particular, on the aft head) and the offset response for hardover failures.

Table 2 summarizes the attenuation resulting from various axis passive failures.

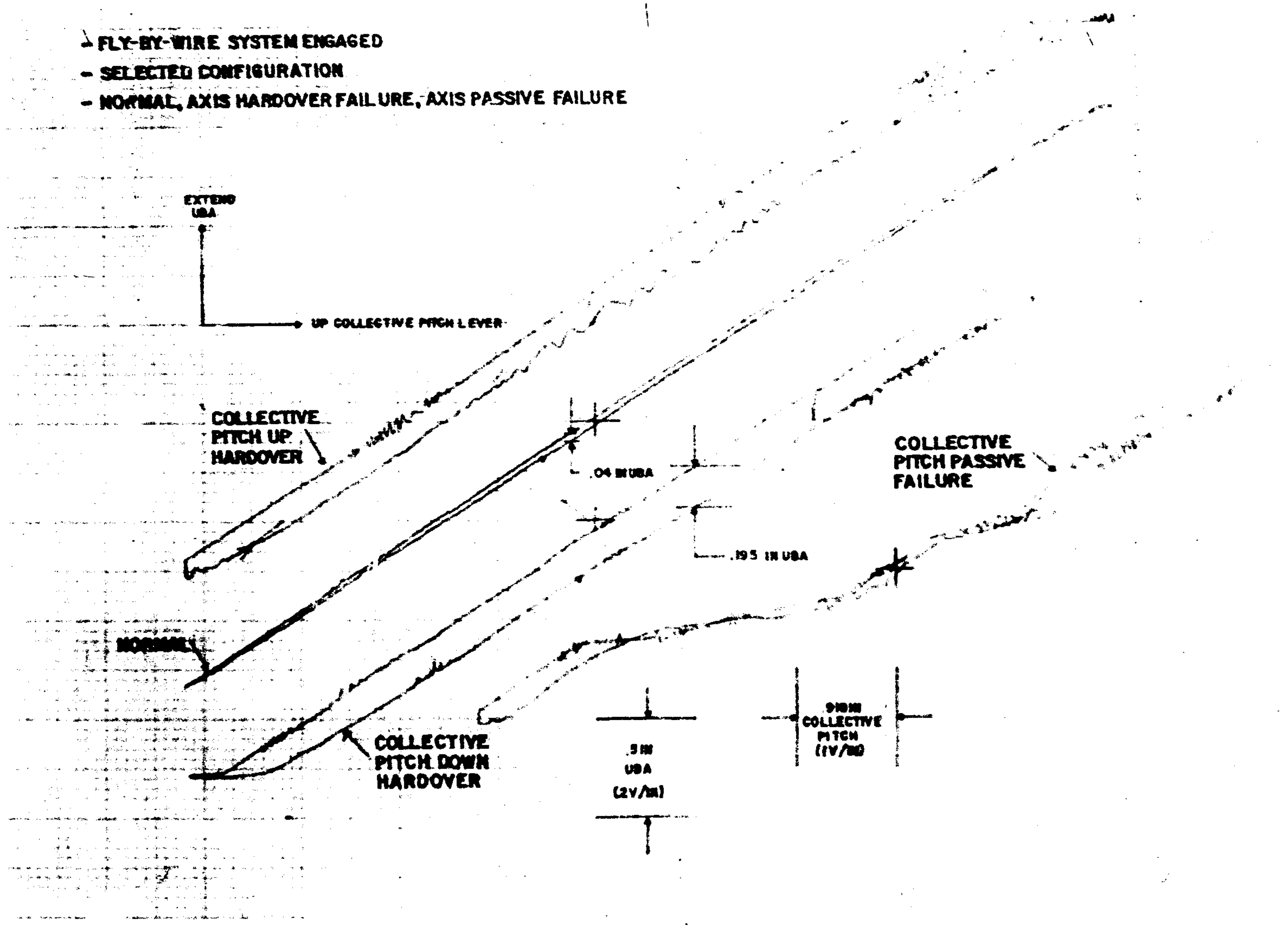


FIGURE 35. AFT LEFT UPPER BOOST ACTUATOR VS COLLECTIVE PITCH AXIS DISPLACEMENT (TP-8)

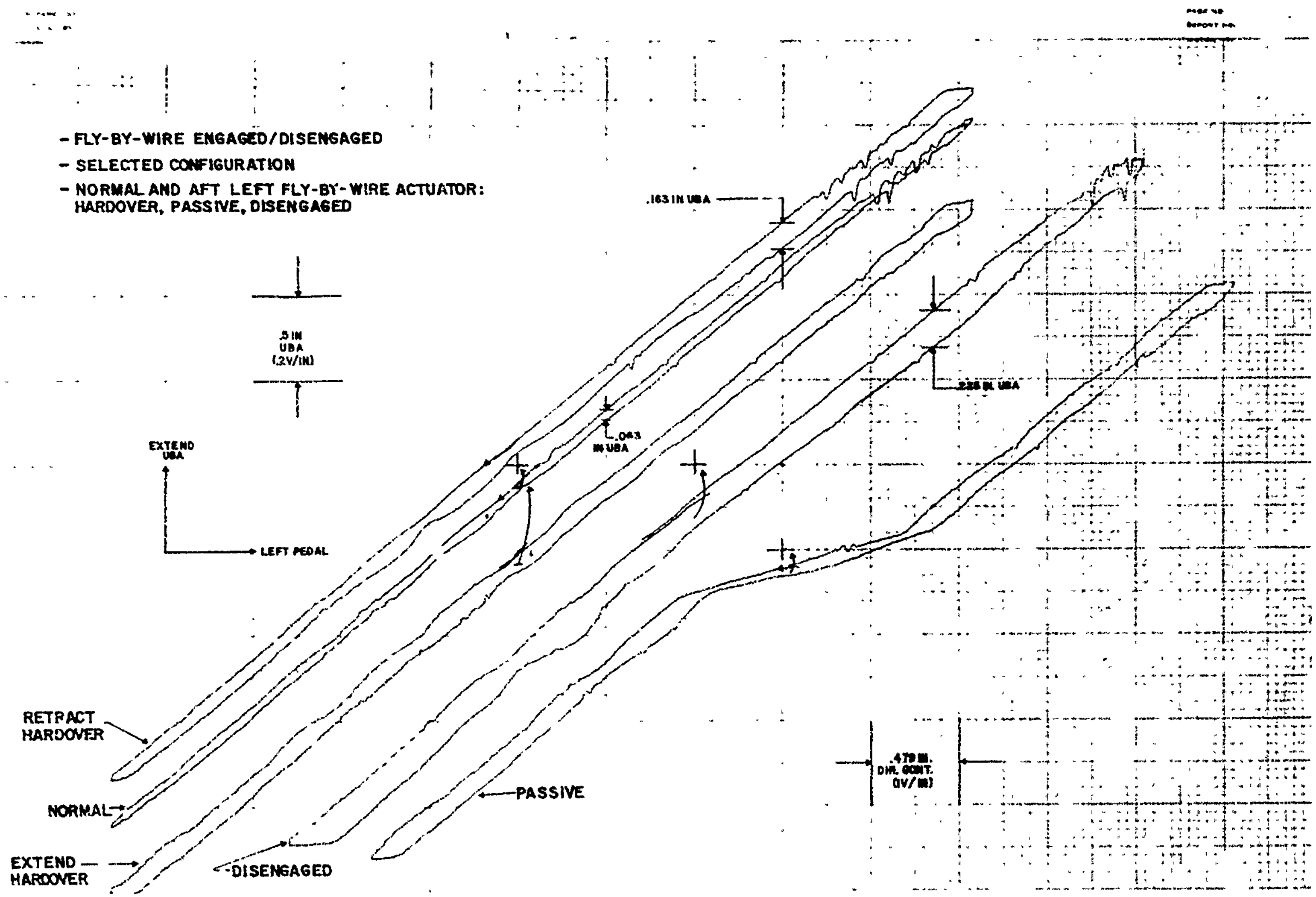


FIGURE 36. AFT LEFT UPPER BOOST ACTUATOR VS DIRECTIONAL AXIS DISPLACEMENT

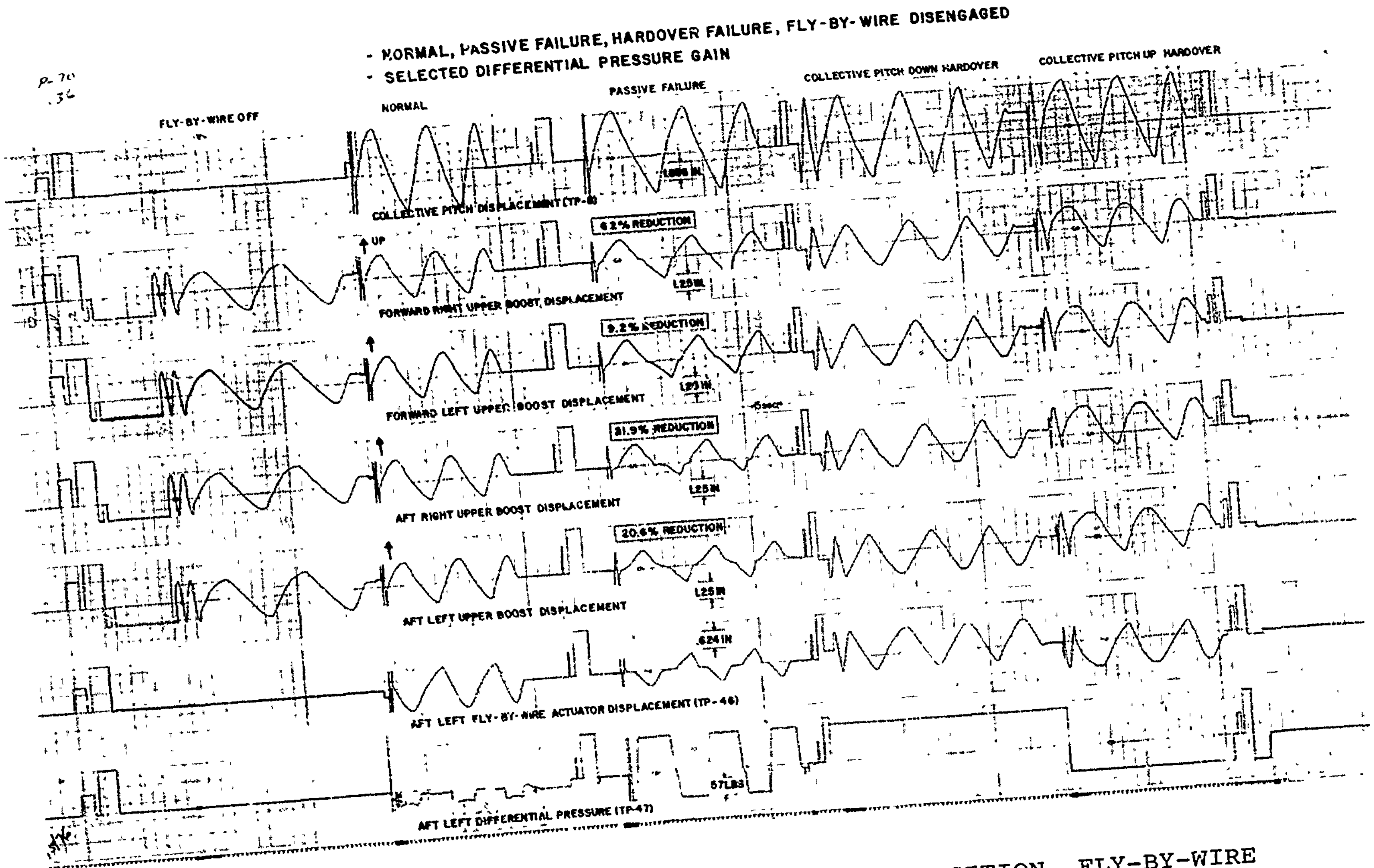


FIGURE 37. TIME HISTORY-UPPER BOOST ACTUATOR POSITION, FLY-BY-WIRE ACTUATOR POSITION COLLECTIVE PITCH CONTROL DISPLACEMENT

TABLE 2. ATTENUATION DUE TO PASSIVE FLY-BY-WIRE ACTUATOR FAILURES

AXIS	UPPER BOOST ACTUATOR ATTENUATION IN PERCENT OF FULL AXIS DISPLACEMENT			
	FORWARD RIGHT	FORWARD LEFT	AFT RIGHT	AFT LEFT
LONGITUDINAL	13	10.6	36.7	40.0
LATERAL	13	8.7	24.6	23.9
DIRECTIONAL	(FBW ACTUATOR OVERPOWERED LOWER BOOST)			
COLLECTIVE PITCH	6.2	9.2	21.9	20.6

Fly-By-Wire Disengaged

When the fly-by-wire channel is disengaged, the mechanical system must move the bypassed actuator. The resulting friction load tends to produce additional hysteresis in the mechanical system response.

Static Performance--The effects of a bypassed actuator can be seen in Figure 36. The hysteresis increased from .063 in. to .225 in. This increase would degrade mechanical system performance slightly, but would have no flight safety impact. In production, the friction of the bypassed actuator would be reduced significantly, thus reducing the hysteresis effect.

Dynamic Performance--Figures 38 and 39 show the response for pitch axis inputs to the aft left actuator with the fly-by-wire bypassed. There is a significant attenuation and increase in phase shift for these inputs. Data is somewhat erratic because the friction tends to vary with frequency. The longitudinal axis is most sensitive to the hysteresis because of its low sensitivity. Under these conditions the pilot might notice some increased activity in the longitudinal axis SAS as it worked through the friction produced/hysteresis. Effects on other axes would be minimal.

This same condition was evaluated as part of the HLH ATC Program when the pilots flew to check out the capability to revert to mechanical backup. The pilots flew on mechanical with no SAS and reported no significant problems in controlling the aircraft. There was a slight increase in activity in the longitudinal axis because of the friction effects.

Open Failures

Response to system open failures at the stick boost output (axis failures) and at the aft actuators was measured for the longitudinal and directional axes.

Static Performance--Effects of open failures on system static performance may be seen in Figures 40 and 41.

Note that in each case the only effect is a small increase in hysteresis. This is probably due to the fact that the fly-by-wire actuators must move against the friction and preload forces normally carried by the mechanical system.

Dynamic Performance--Effects of system opens on dynamic performance are shown in Figures 42 through 45. The effects of added friction are most noticeable in the longitudinal axis response. The larger amplitude directional axis responses are good at the baseline mechanical system data as shown in Figures 25 and 26.

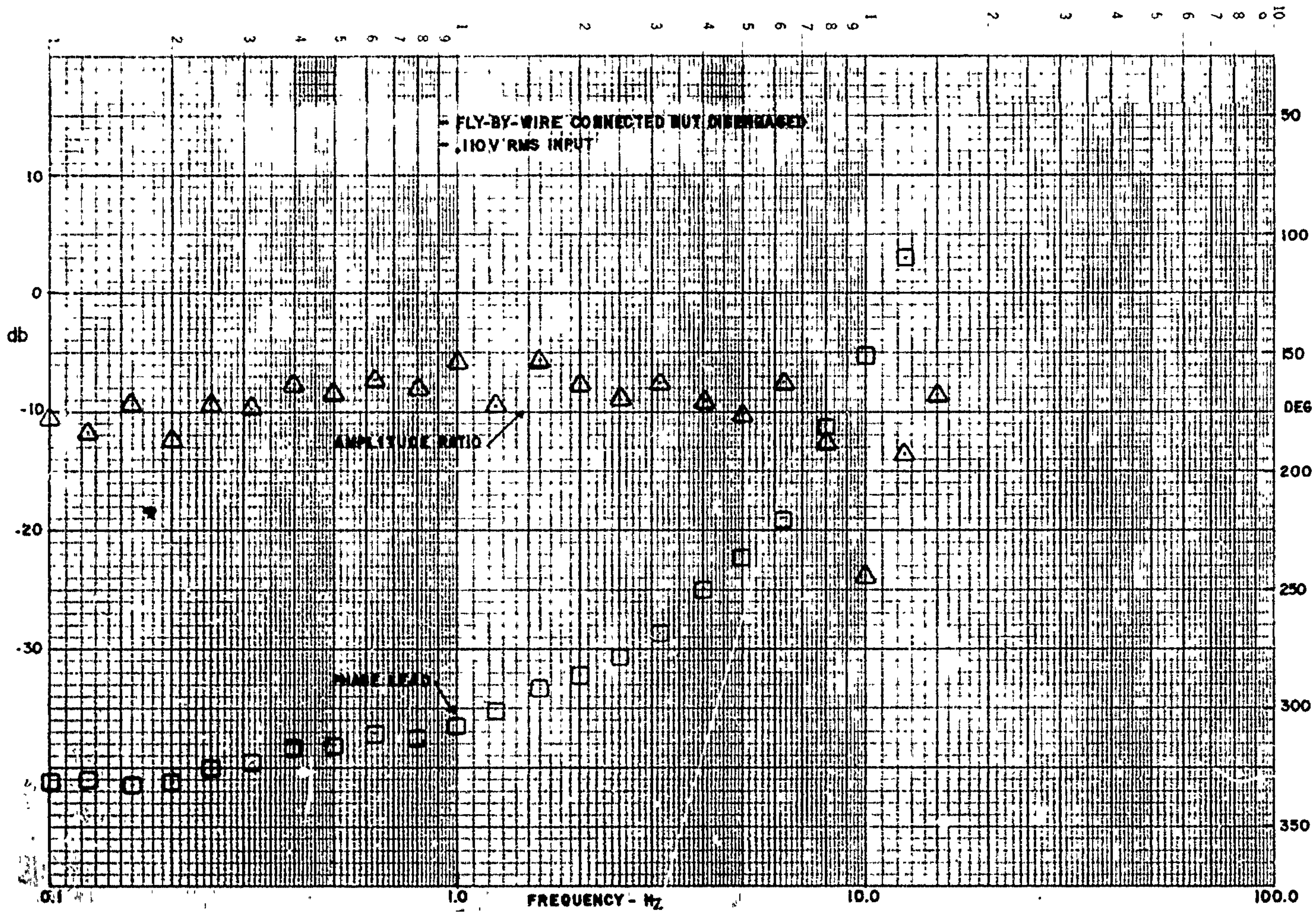


FIGURE 38. FORWARD RIGHT UPPER BOOST ACTUATOR VS LONGITUDINAL SAS COMMAND

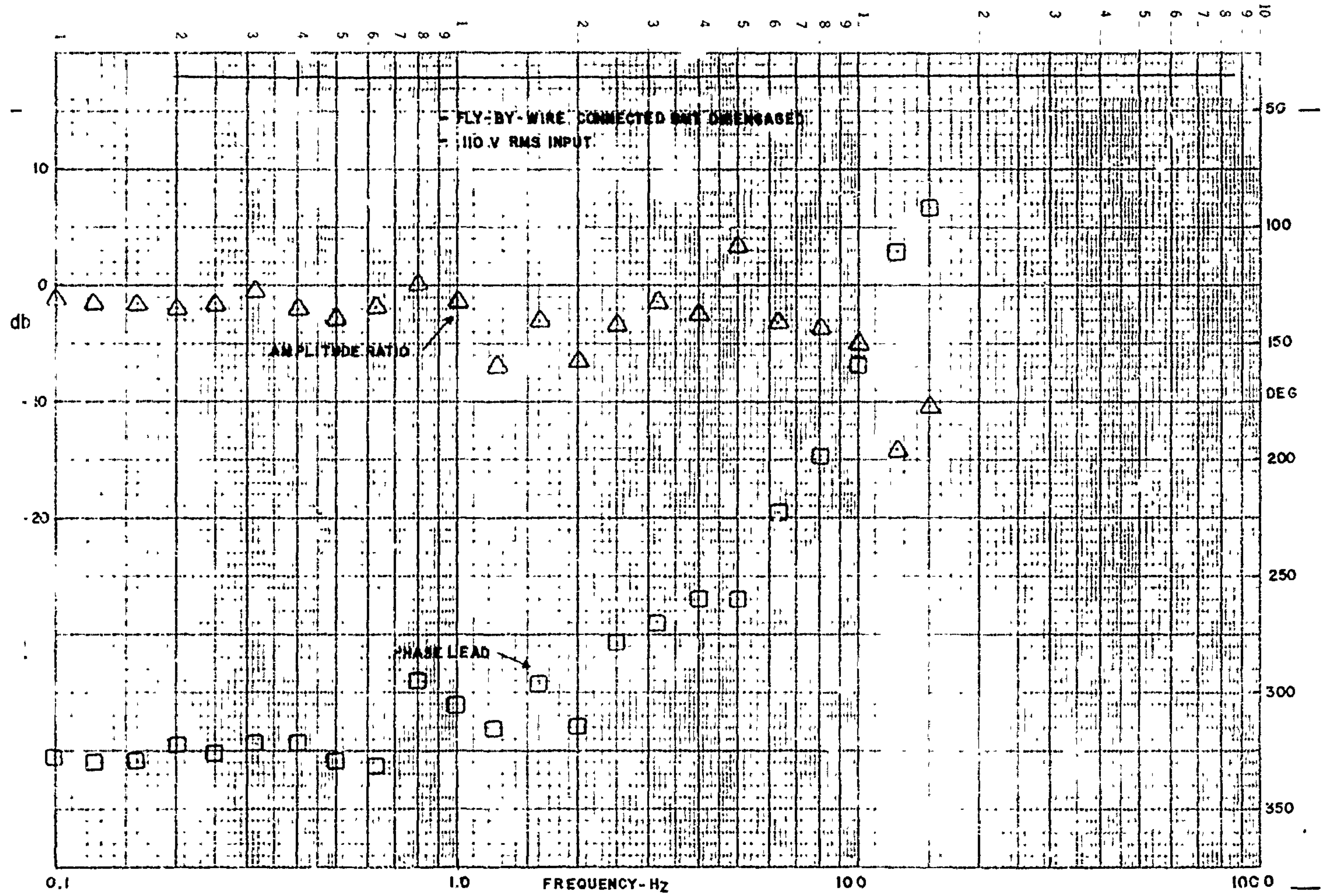


FIGURE 39. AFT LEFT UPPER BOOST ACTUATOR VS LONGITUDINAL SAS COMMAND

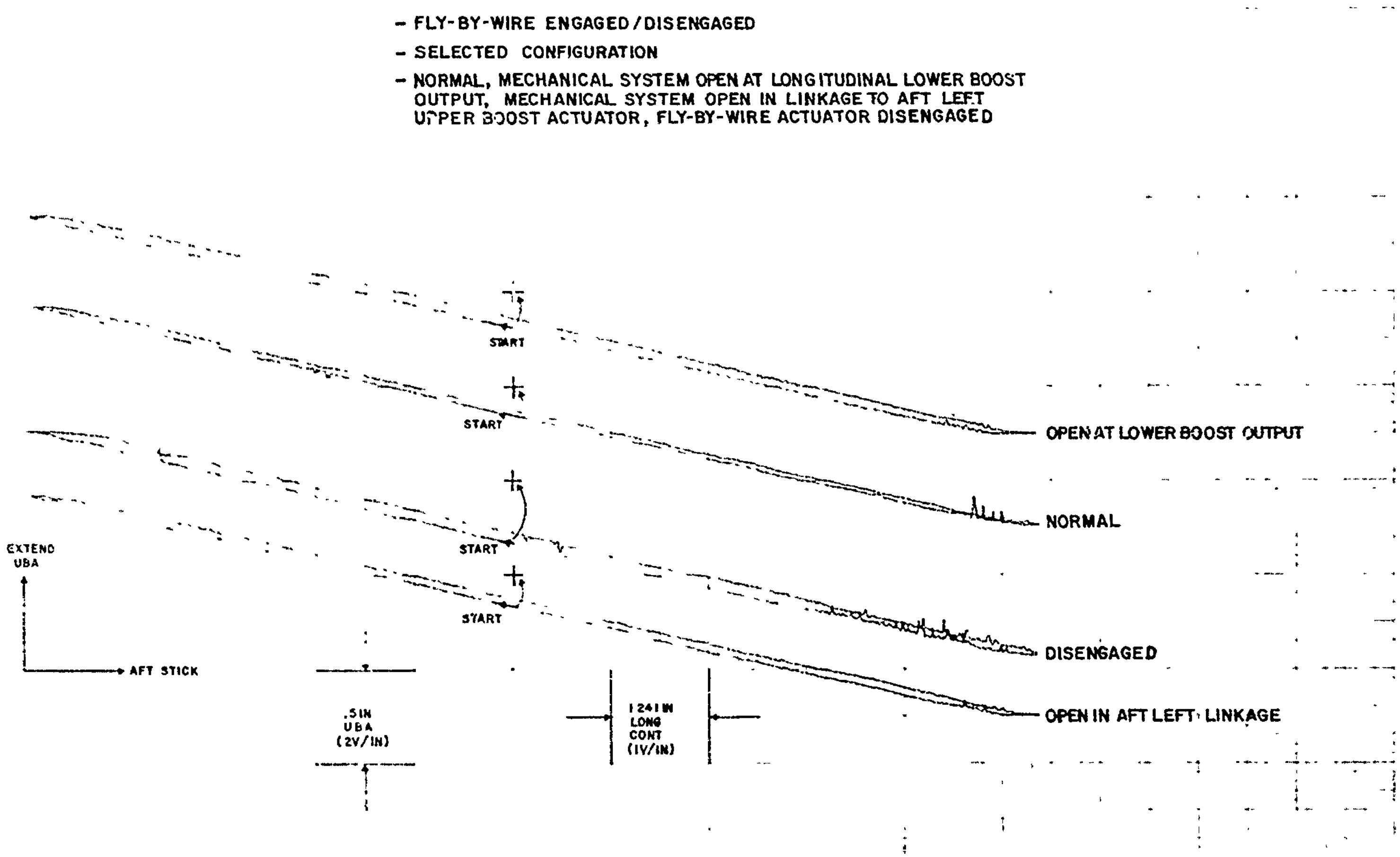


FIGURE 40. AFT LEFT UPPER BOOST ACTUATOR VS LONGITUDINAL AXIS DISPLACEMENT (TP-10)

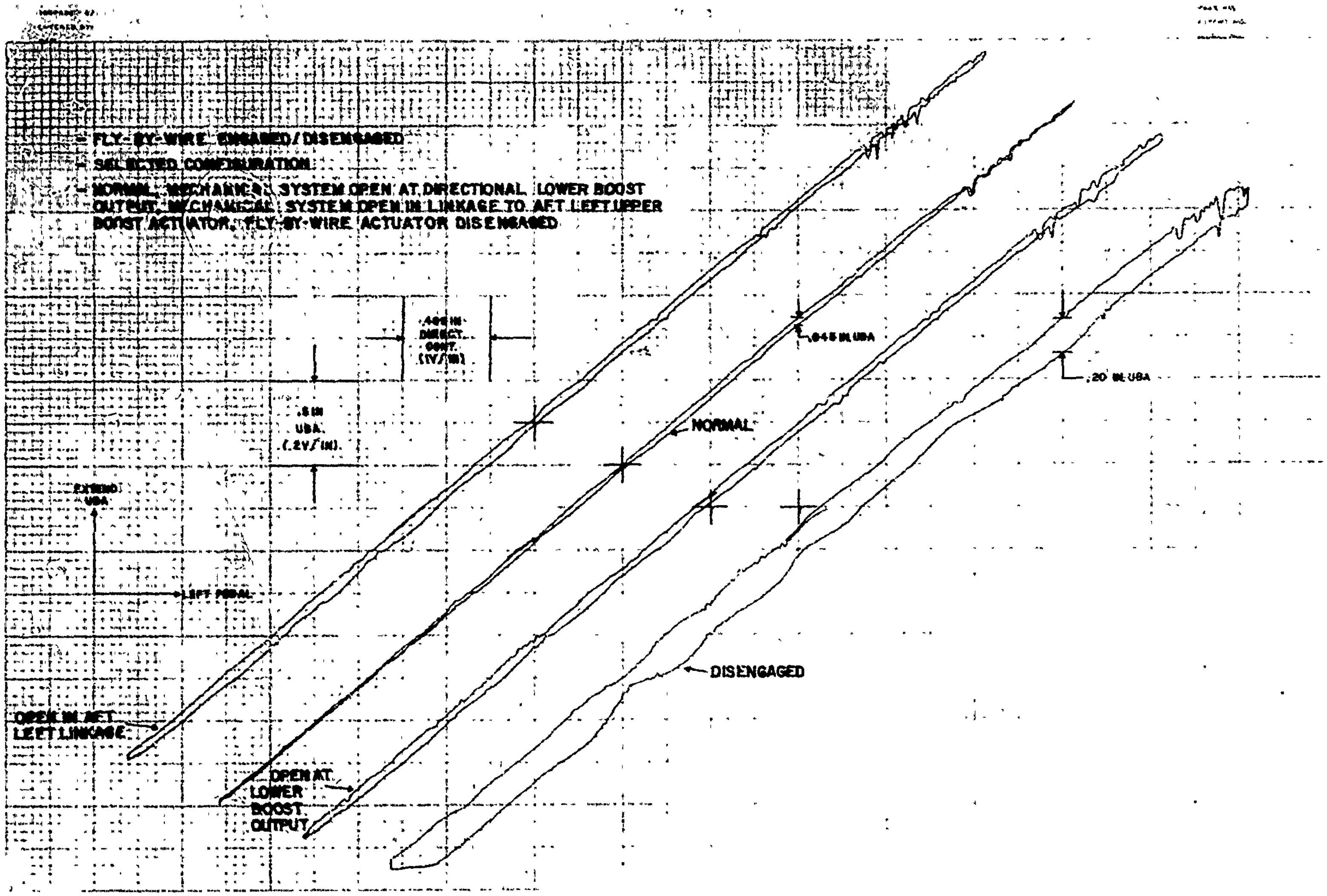


FIGURE 41. AFT LEFT UPPER BOOST ACTUATOR VS DIRECTIONAL AXIS DISPLACEMENT (TP-13)

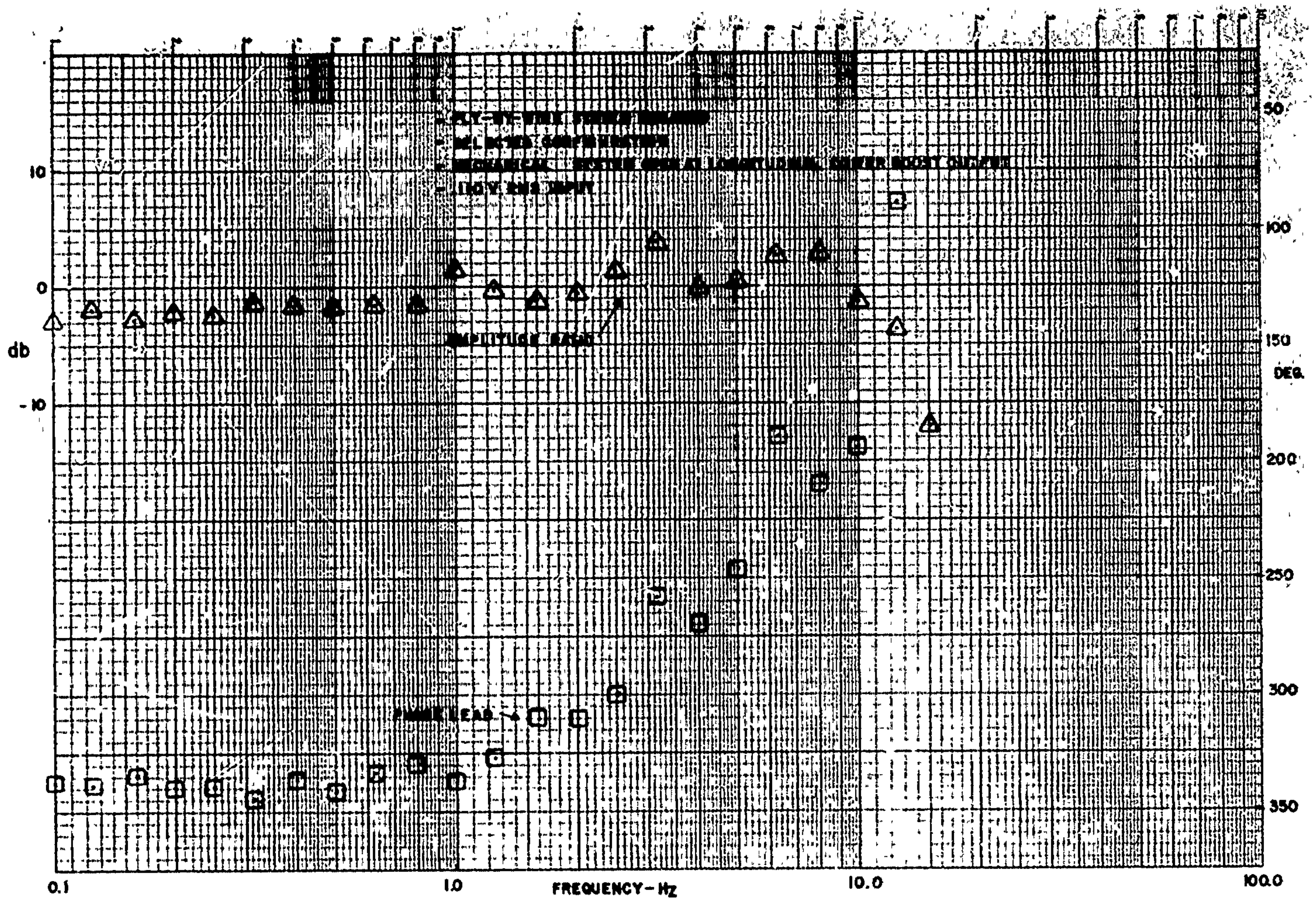


FIGURE 42. AFT LEFT UPPER BOOST ACTUATOR VS LONGITUDINAL SAS COMMAND

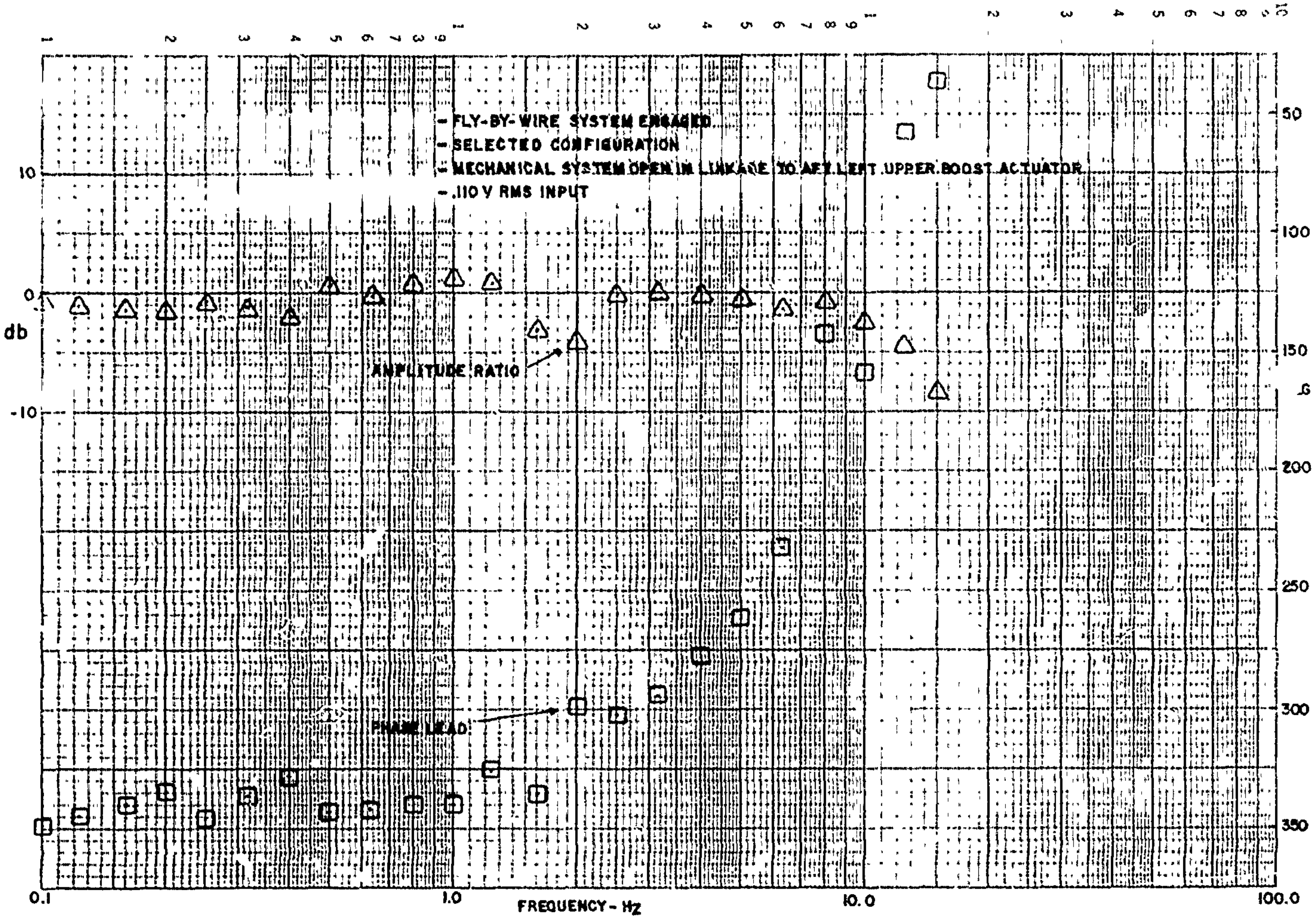


FIGURE 43. AFT LEFT UPPER BOOST ACTUATOR VS LONGITUDINAL SAS COMMAND

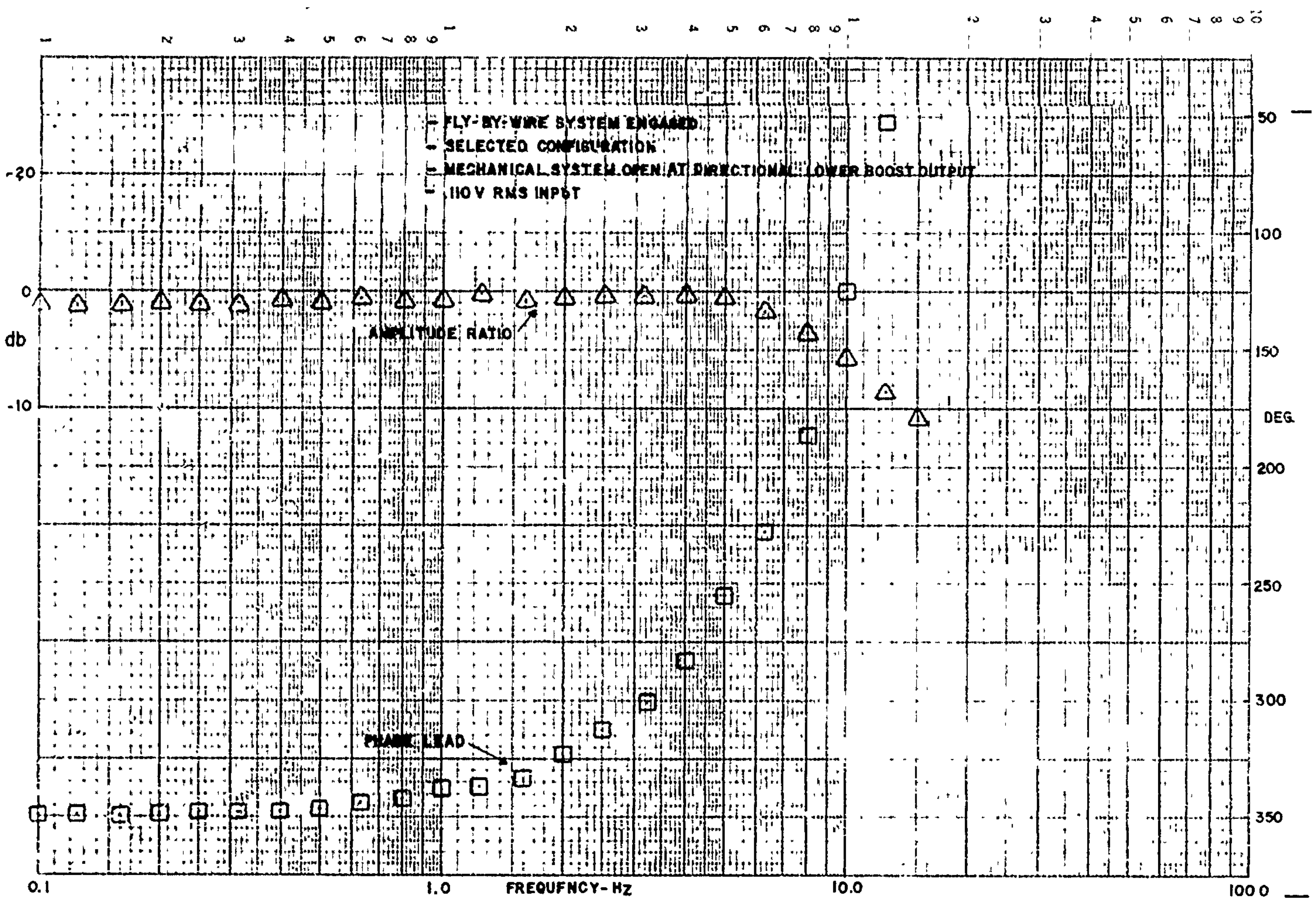


FIGURE 44. AFT LEFT UPPER BOOST ACTUATOR VS DIRECTIONAL SAS COMMAND

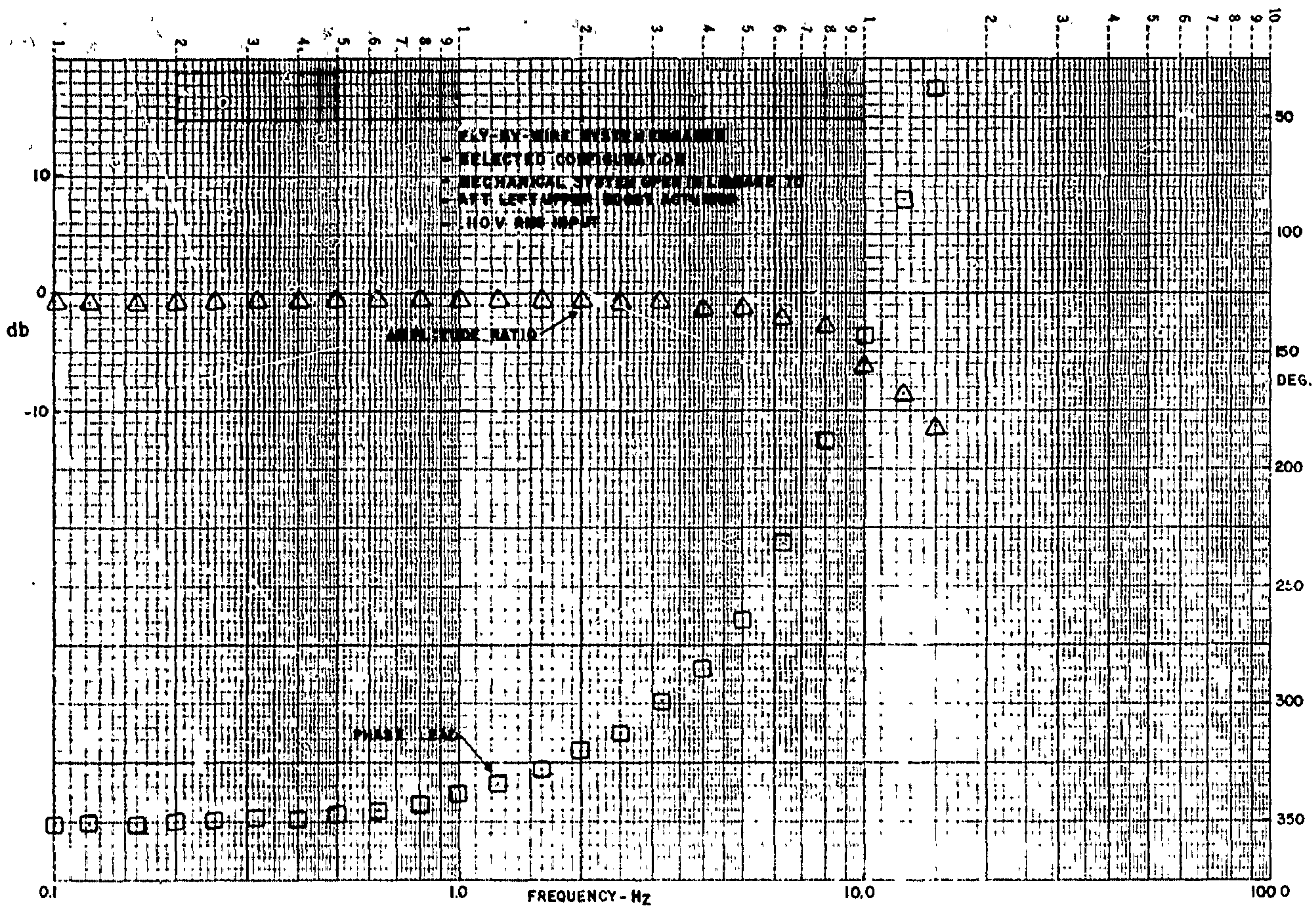


FIGURE 45. AFT LEFT UPPER BOOST ACTUATOR VS DIRECTIONAL SAS COMMAND

INTERFACE TECHNIQUE ANALYSIS

Selected Configuration

Based on the testing conducted in this program, a low gain differential pressure feedback compensated configuration with a longitudinal axis monitor and with delayed automatic shutdown was selected for the following reasons:

1. Softening of the FBW stiffness is necessary to achieve adequate compensation for mistrack between mechanical and electrical FBW systems. The alternatives would be to soften the mechanical system, which would further degrade performance in the FBW disengaged case or provide a completely self-monitored FBW channel so that failures could be detected independently of force fights. This would increase system costs.

2. At the differential pressure selected, the demonstration system shows performance which is comparable and in some cases, superior to that achieved by the mechanical system alone. Figures 46 through 53 show dynamic performance comparisons for longitudinal and directional axis SAS inputs of ±10 percent and ±20 per cent. For the small amplitude pitch axis response, performance of the FBW is superior on the aft head where the FBW can overcome the dead band in the mechanical system which attenuates the small displacement. Figures 33 and 34 show that the static response is comparable with the baseline shown on Figures 19 and 20.

3. A dualized longitudinal axis is recommended to minimize the transient, especially for cases where one SAS is off.

4. Automatic shutdown with a delay is recommended because of the attenuation of response in the presence of a FBW actuator passive failure. A time delay of from 3 to 4 seconds should be adequate to minimize nuisance trips due to dynamic inputs.

Actuator Stall Force Capability

For a production system, the FBW driver actuator force capability would be limited to approximately 50 lb relative to the upper boost actuator input. This will ensure that the most critical directional axis lower boost would be able to overcome an axis hardover, assuming both flight control hydraulic boost systems are functional. Normally, of course, the failure would be shut down by the force fight detector. As noted previously, this will reduce the failure effects seen in this demonstration by a factor of 50/93 so that failure time delays will increase.

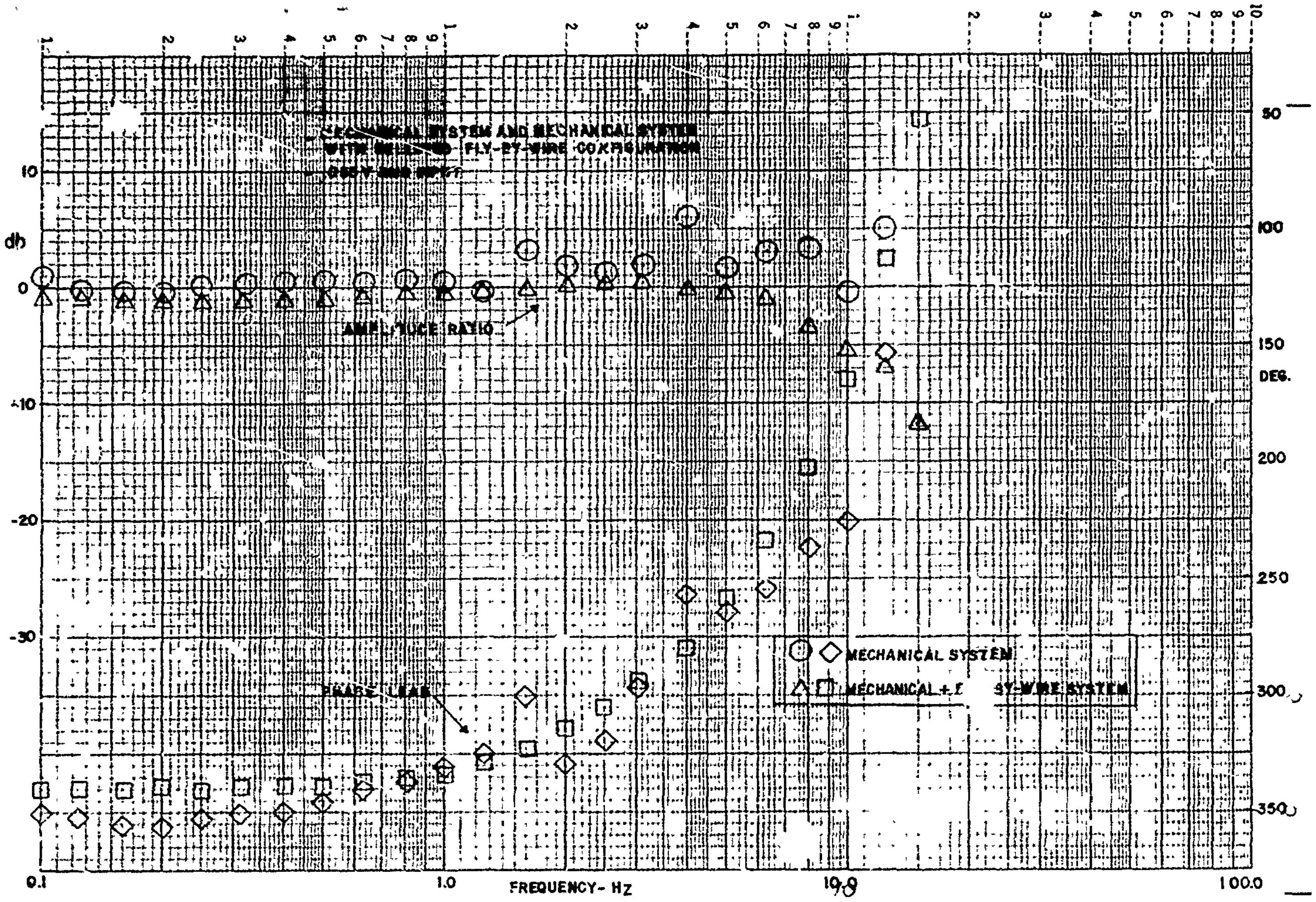


FIGURE 46. FORWARD RIGHT UPPER BOOST ACTUATOR VS LONGITUDINAL SAS COMMAND

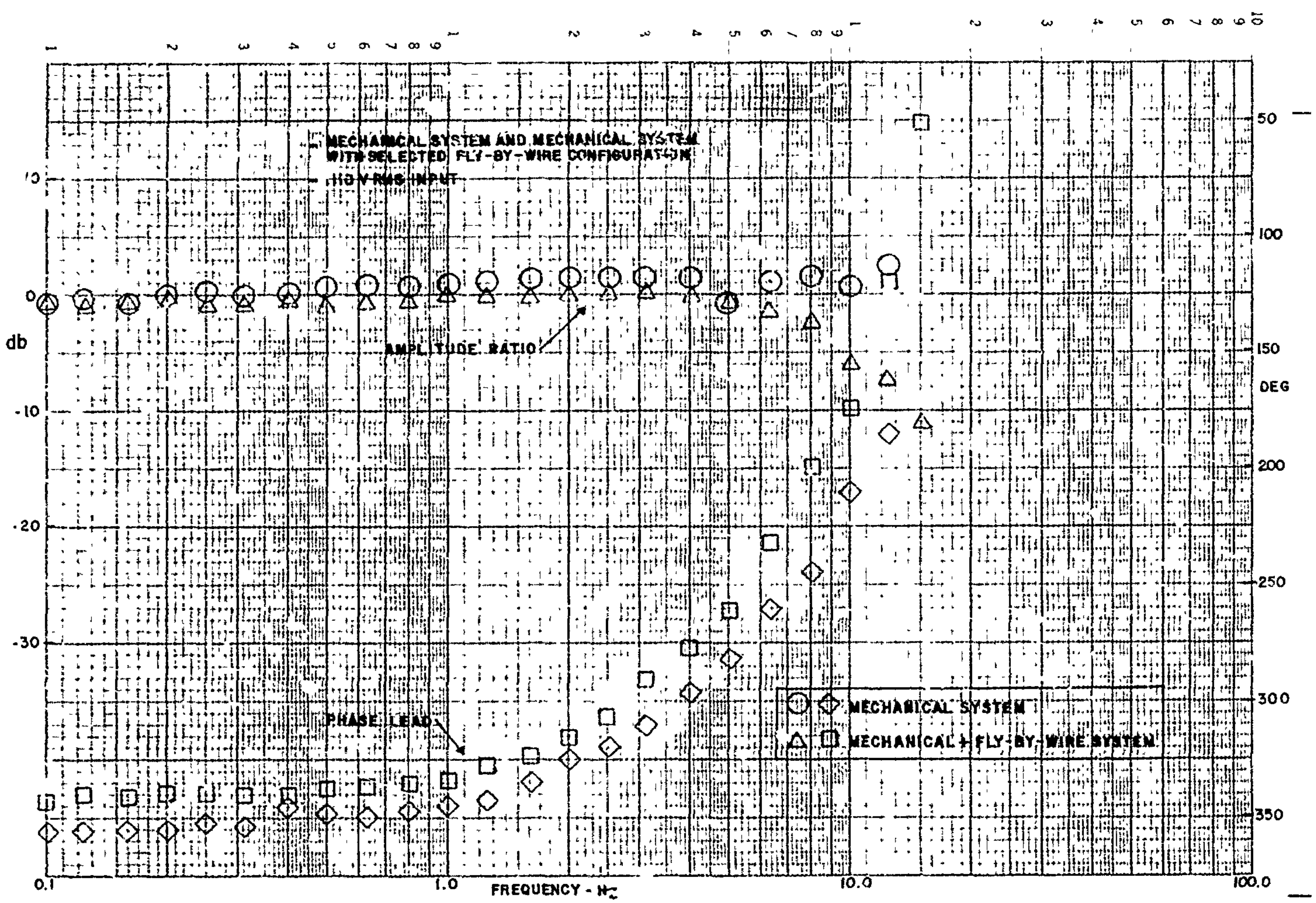


FIGURE 47. FORWARD RIGHT UPPER BOOST ACTUATOR VS LONGITUDINAL SAS COMMAND

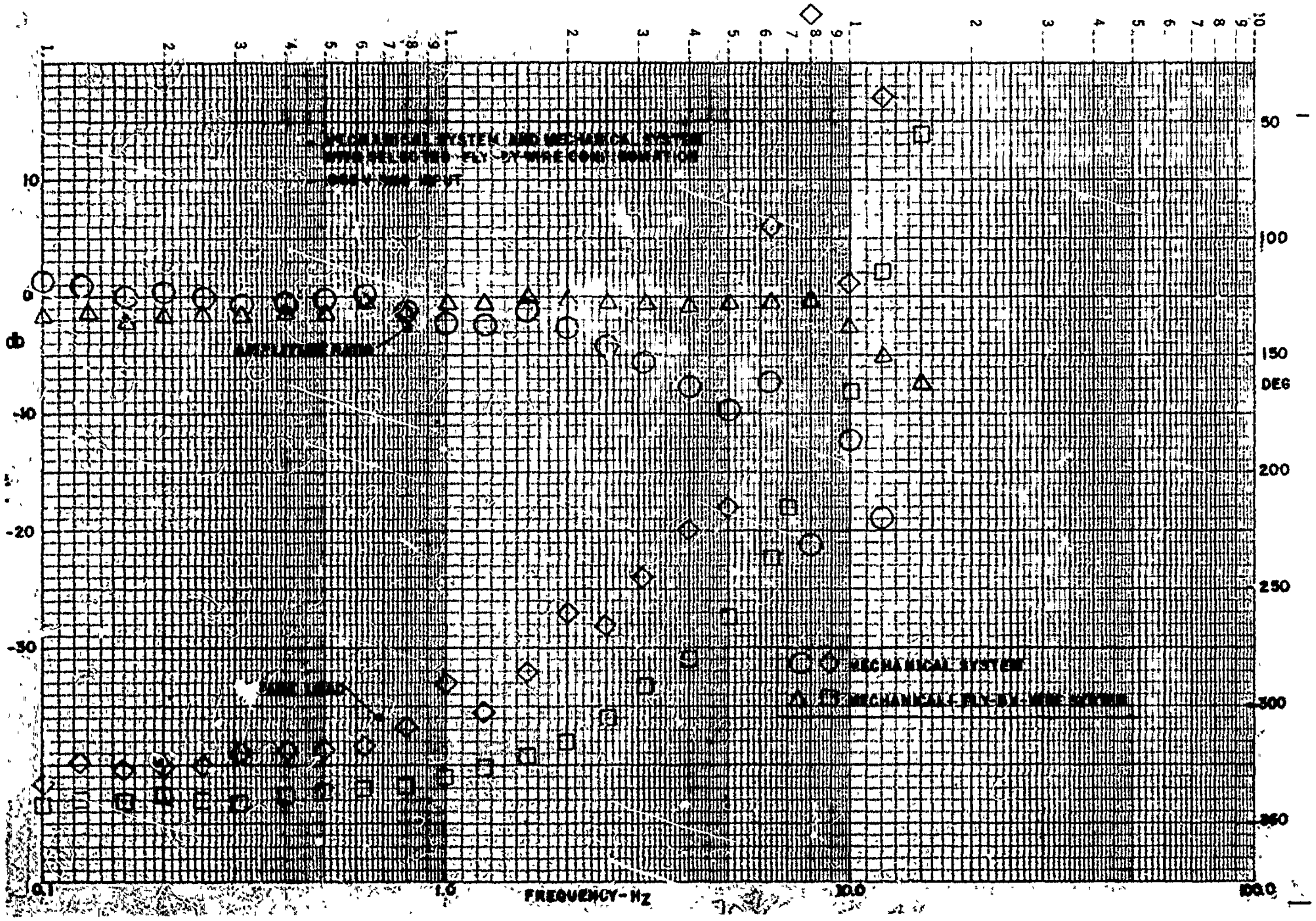


FIGURE 48. AFT LEFT UPPER BOOST ACTUATOR VS LONGITUDINAL SAS COMMAND

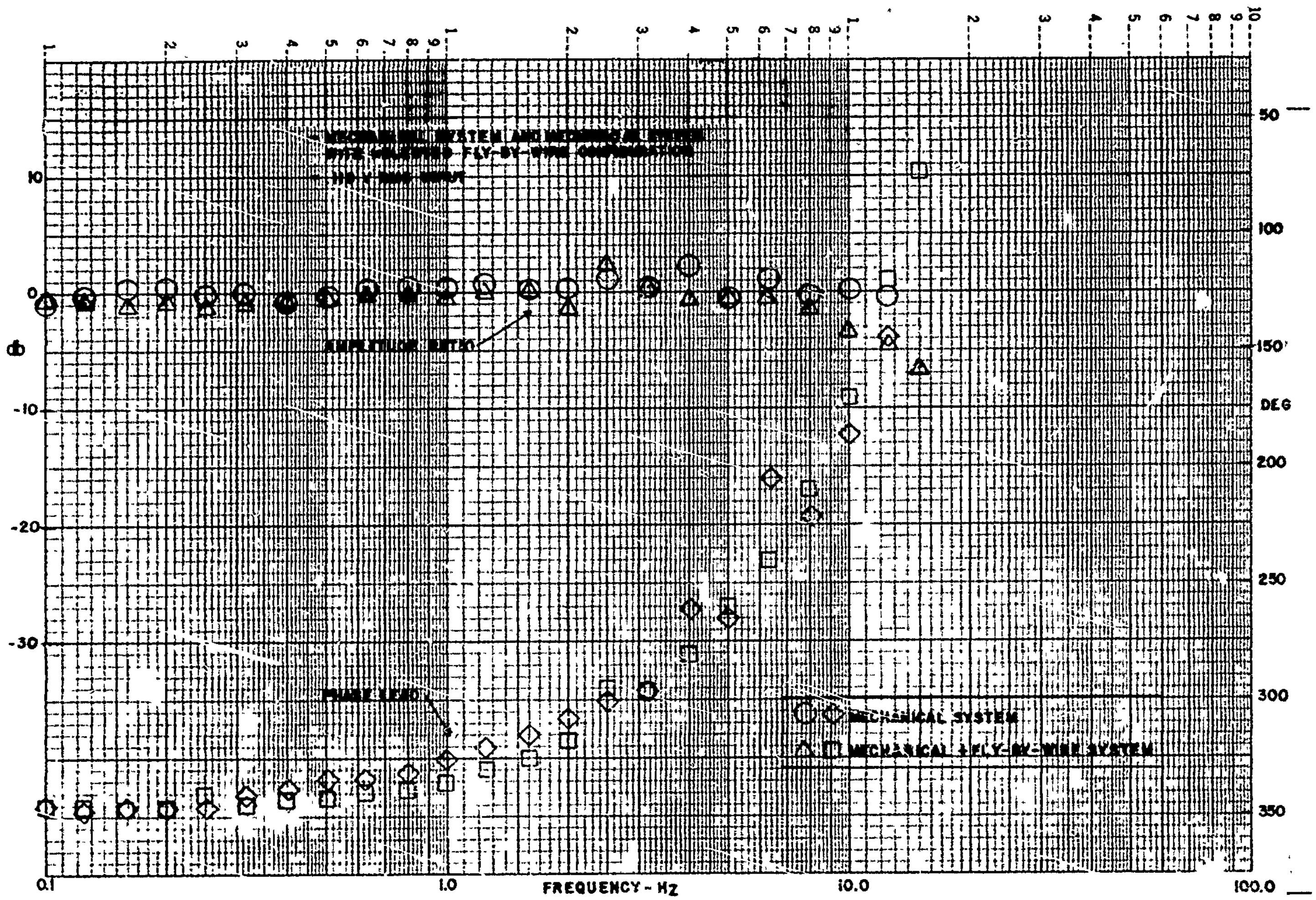


FIGURE 49. AFT LEFT UPPER BOOST ACTUATOR VS LONGITUDINAL SAS COMMAND

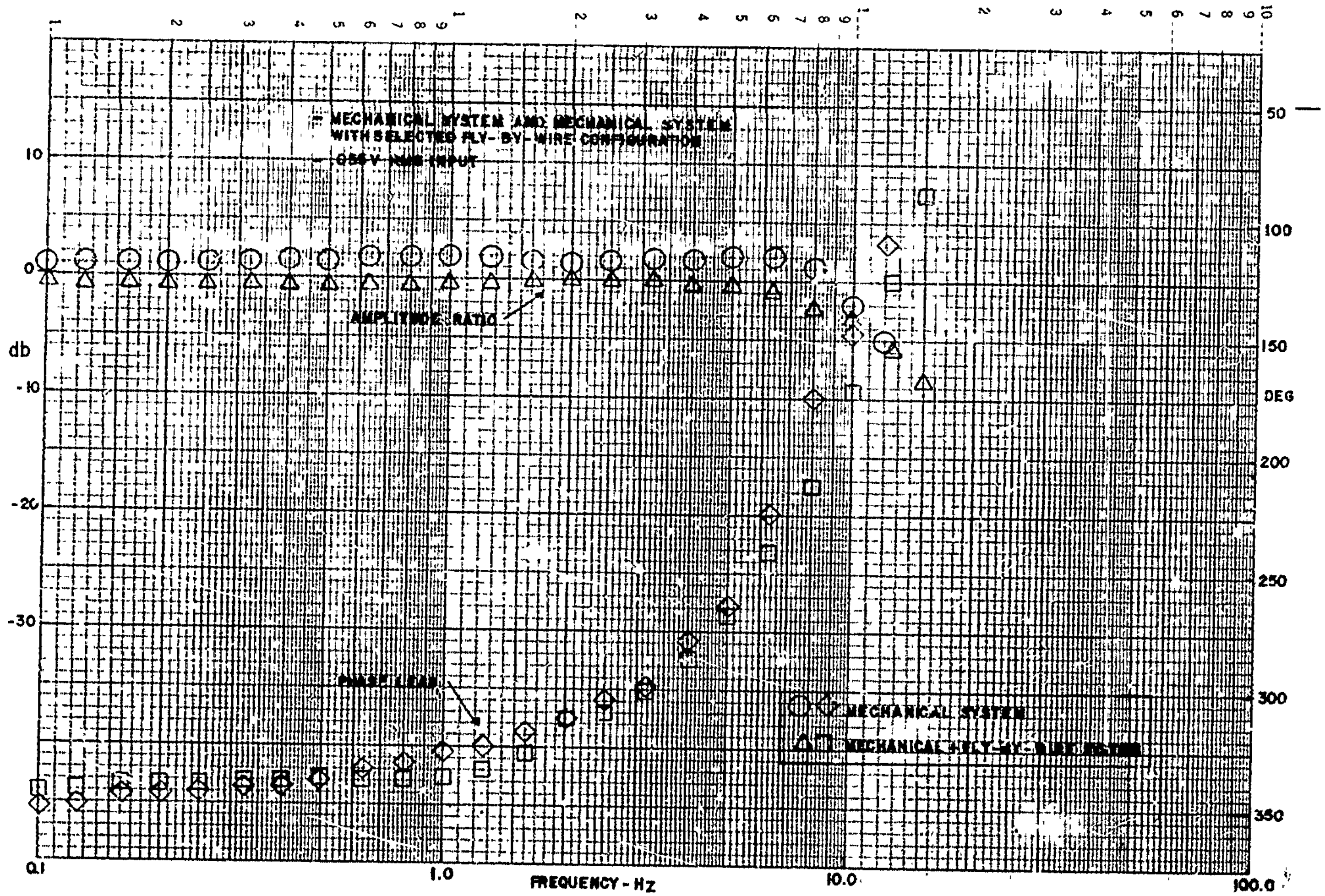


FIGURE 50. FORWARD RIGHT UPPER BOOST ACTUATOR VS DIRECTIONAL SAS COMMAND

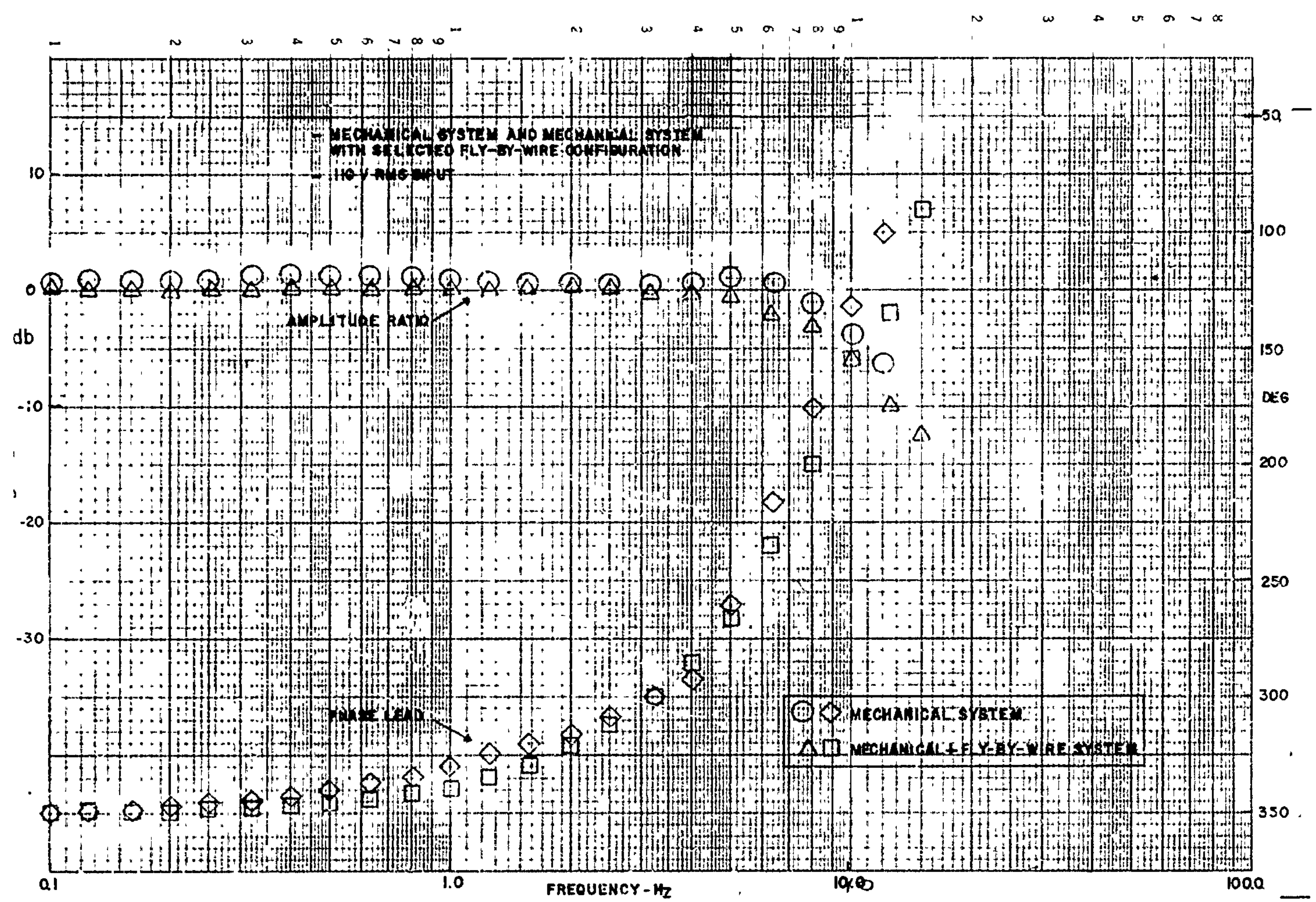


FIGURE 51. FORWARD RIGHT UPPER BOOST ACTUATOR VS DIRECTIONAL SAS COMMAND

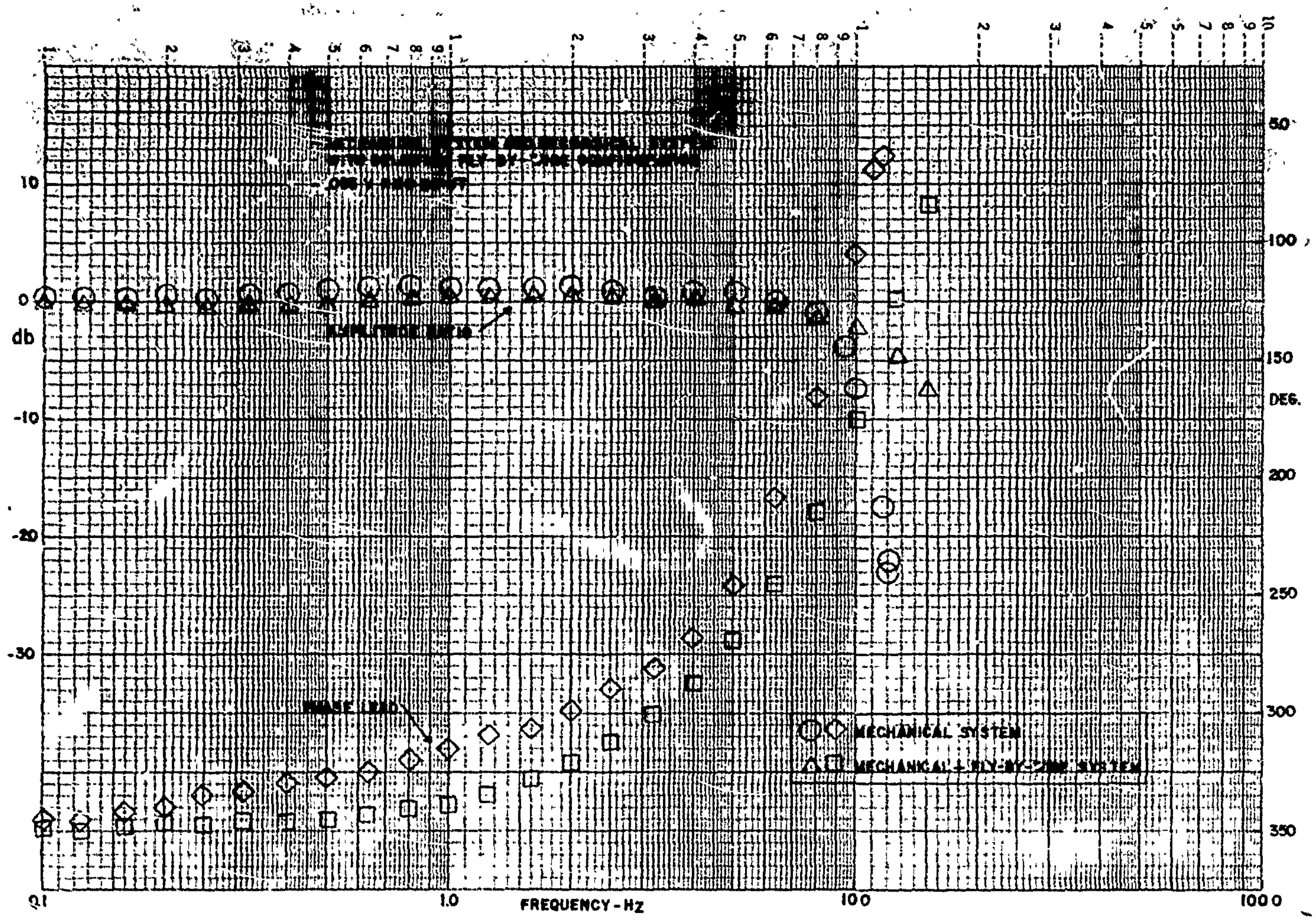


FIGURE 52. AFT LEFT UPPER BOOST ACTUATOR VS DIRECTIONAL SAS COMMAND

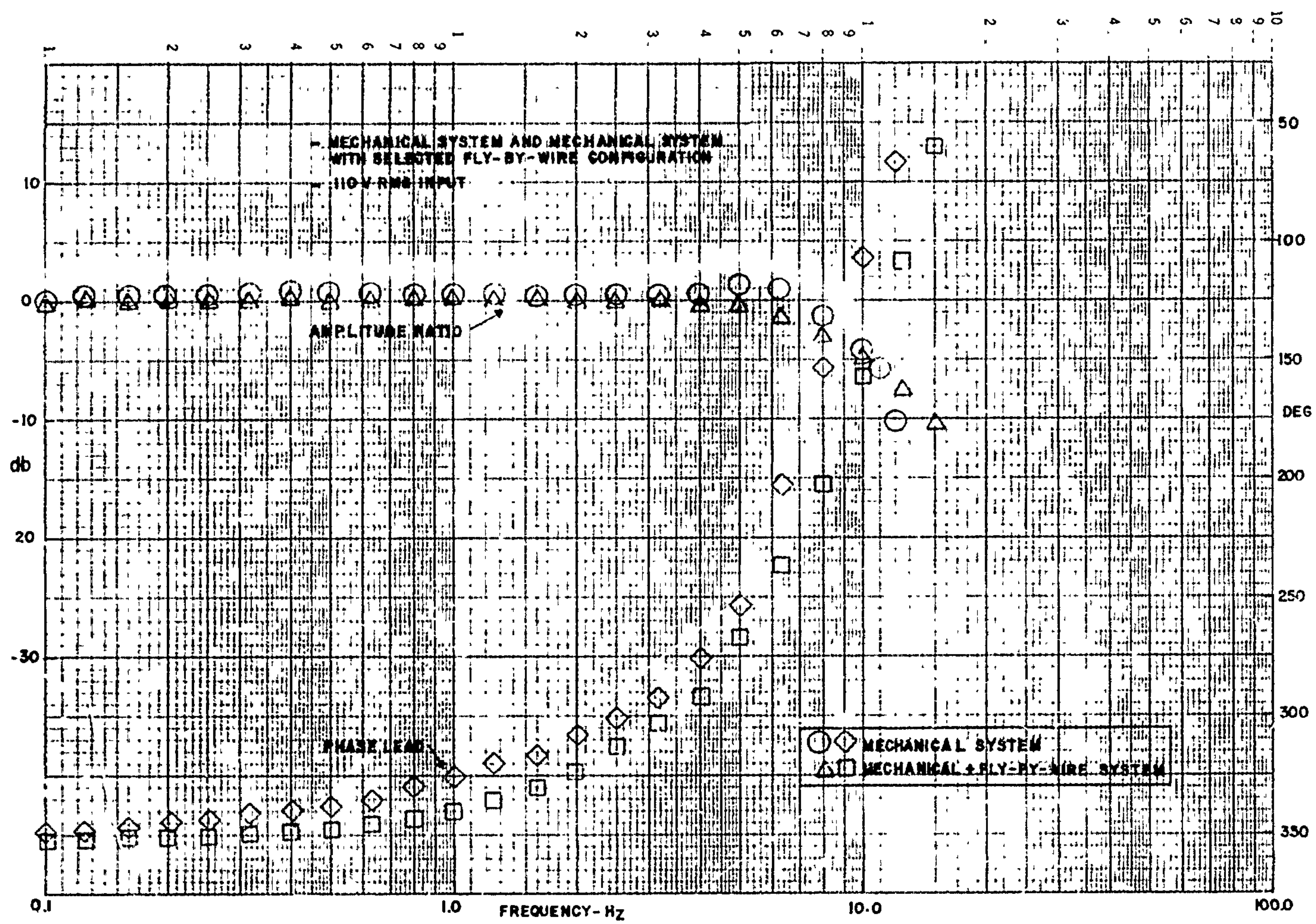


FIGURE 53. AFT LEFT UPPER BOOST ACTUATOR VS DIRECTIONAL SAS COMMAND

Error Accumulation Vs. Compensation Displacement

Errors in tracking between the two systems result from gain and null variations in each of the systems. Possible variations have been estimated based on tolerances allowed for the electrical channels of the HLH ATC and a quick check of tolerances in the mechanical system. Null offsets of the mechanical system with temperature remain to be evaluated.

In the HLH ATC the criterion used for failure detection level was:

Failure Detect Level = 2 x the 3-sigma mistrack between channels

The 1-sigma variation between the systems can be expressed as:

$$\sigma_{ELECT-MECH} = \sqrt{\sigma_{ELECT}^2 + \sigma_{MECH}^2}$$

Variation due to the electrical system tolerances is made up of contributions from each axis and a null offset term as shown in Table 3. A gain tolerance of 2 percent is assumed for each axis input with an assumed null tolerance of 0.8 per cent. These tolerances are assumed to be 3-sigma values for each component of error. Thus the σc value is defined as:

$$(3\sigma_C)/3$$

The 1-sigma value for the combination may be expressed as:

$$\sigma_{ELECT} = \sqrt{\Sigma\sigma_C^2/n}$$

where n = number of components making up the combination. In this case, n = 5 because we have 4-gain and 1-null contributions. We further assume that the mechanical system has similar tolerances. Based on the above, we calculate the 3-sigma difference between the systems as:

$$3\,\sigma_{ELECT-MECH} = 3\sqrt{2\,\Sigma\sigma_C^2/5}$$

where σ_C is 49.181×10^{-5}-in.^{2} as defined in Table 3. By the previous criteria then, the fail-detect displacement is:

$$F_D = 2 \times 3\sigma_{ELECT-MECH}$$

solving for F_D yields F_D = .084-in. of upper boost displacement. This displacement must produce approximately the stall capacity of the actuator (assumed to be 50-lb). Data shows that friction loads on the actuator may produce up to 25-lb force so it is conservative to reduce the effective trip force to 25-lb. The resulting stiffness required between systems is:

TABLE 3. DERIVATION OF 3-SIGMA VARIATION IN FLY-BY-WIRE ACTUATOR POSITION FOR COMBINED AXIS INPUT.

AXIS/ACTUATOR	FULL AXIS TRAVEL IN CH-47C UPPER BOOST	DISPLACEMENT (IN.) DUE TO 2% GAIN ERROR AT 2/3 AXIS DISPLACEMENT ($3\sigma_C$)	$(3\sigma_C/3)^2$
LONGITUDINAL	± .727	.0097	1.045×10^{-5}
LATERAL	±1.70	.0226	5.675×10^{-5}
DIRECTIONAL	±2.44	.0330	12.100×10^{-5}
COLLECTIVE PITCH	±1.55	.0207	4.761×10^{-5}
ACTUATOR NULL	-----	.0480	25.600×10^{-5}
		.1340 WORST CASE ERROR	49.181×10^{-5} $\Sigma(3\sigma_C/3)^2$

$$K_{EFF} = 25/.084 = 298\text{-lb/in.}$$

Data taken during testing shows the stiffness at the FBW actuator output with selected differential pressure feedback gains to be as follows:

1. FBW Actuator Stiffness - 3,727-lb/in.
2. Aft Mechanical System - 751-lb/in.
3. Forward Mechanical System - 1,967-lb/in.

By combining the spring rates in series and relating to the upper boost actuator input as a reference point, we get the following effective stiffness between systems:

1. Forward Head - 335-lb/in.
2. Aft Head - 167-lb/in.

These values compare favorably with the required stiffness of 298-lb/in. This means that there will be a low probability of nuisance trips if the systems have the gains and nulls assumed.

There is some margin for further softening of the electrical actuator stiffness without compromise of performance, because the friction of the production actuator will be lower than that of the actuator us in the demonstration system.

LOWER BOOST DEPRESSURIZATION AND BYPASSING TESTING

Normal Operation

Response of the system with longitudinal and lateral lower boost actuators depressurized was evaluated. Longitudinal response was normal. Lateral response forces were increased with friction effects apparent in that the centering springs failed to return the lateral stick to trim position when the stick was released after being displaced.

FBW Off

Response with FBW off was degraded in longitudinal with failure to return to trim after displacement. Lateral forces were excessive and control would probably be lost.

Open Mechanical System and Driver Hardover

Due to the fact that system operation with the system connected was not acceptable, there was no point in evaluating these conditions.

System Stability

There was no tendency to instability. Feedback of SAS inputs to the cockpit controls through depressurized lower boost actuators was apparent and annoying. Negative effects might be minimized by reducing system friction. Based on the above results, it was concluded that this elimination of the lower boost is impractical.

SYSTEMS ASSESSMENT

Table 4 summarizes the impact of a FBW backup system installation on a CH-47C helicopter. Data reflects value originally predicted under Contract DAAJ02-74-C 0052 and revised estimates based on results of current contractual effort. Assessment follows ground rules established in Boeing Vertol Document D210-10849-1, "Design and Analysis of Vulnerability-Reduction Measures for the CH-47C Helicopter".

PERFORMANCE

Data shown is based on Boeing document 114-PJ-7103, CH-47C Model Specification, dated May 1974. The following notes relate to the data shown:

1. Data is valid for either an internal or an external load based on a 33,000-lb gross weight aircraft. Effect of change is either on payload or on range for a constant gross weight aircraft, not on both.

2. Agility is based on an ASE equipped aircraft flying at a GW increase/decrease equal to the ASE equipment weight.

3. Fuel flow rate is based on an ASE equipped aircraft flying at a gross weight increase/decrease equal to the ASE equipment weight.

RELIABILITY

The reliability analysis considered the impact of the changes on maintenance reliability expressed in failures per flight hour and mission/flight safety reliability in failures per flight hour considering a 1-hour mission.

MAINTAINABILITY

The maintainability analysis, which included unscheduled maintenance and scheduled inspection, estimated the effect of the changes in each area. The unscheduled maintenance was measured in man-hours expended per 1,000 flight hours and was determined by applying the maintenance-malfunction rate (determined in the reliability analysis) to the applicable current task times to perform repairs. Scheduled inspection was measured in man-hours per 1,000 flight hours and was determined by applying the inspection frequency (progressive phased-inspection concept) to the task times outlined in the inspection document. In both cases, task times for new items or new requirements were extrapolated from task times of existing similar items or conditions.

TABLE 4. SYSTEMS ASSESSMENT SUMMARY
(ALL VALUES EXPRESSED IN TERMS OF
EFFECT ON CH-47C PARAMETERS)

EFFECT ON	PREDICTED UNDER CONTRACT DAAJ02-74-C-0052	REVISED ASSESSMENT	CHANGE IN ASSESSMENT
RELIABILITY			
- Maintenance Rate/Flight Hour	+0.0021307	+0.0041920	+.0020613
- Mission Rate Change for 1-Hour Mission	+0.000415675	+0.000918	+.0005023
- Flight-Safety Rate Change for 1-Hour Mission	-0.0000015324	NEG.	NEG.
MAINTAINABILITY			
- Scheduled MMH/1000 FH	+1.812	+3.769	+1.957
- Urscheduled MMH/1000 FH	+1.437	+4.046	+2.609
- Total MMH/1000 FH	+3.249	+7.815	+4.566
AVAILABILITY			
- Unscheduled Maintenance	-0.1707%	-0.3470%	- .176%
- Scheduled Maintenance	-0.12756%	-0.3813%	- .254%
- Total	-0.29826%	-0.7283%	-0.430%
PERFORMANCE			
- Payload Change	+109-lb	+128	+19
- Range	+ 5.4 mm	+ 5.7 mm	+ 0.3 mm
- Speed	NO CHANGE	NO CHANGE	NO CHANGE
- Agility	+ 21.8 fpm	+ 24.6 fpm	+ 1.8 fpm
- Fuel Flow Rate	- 2.7 lb/hr	- 3.0 lb/hr	- 0.3 lb/hr
WEIGHT	-109 lb	-128 lb	-19 lb
COST			
- RDT&E	1.625 M	1.925 M	+ 0.3 M
- 250 Kits	11.076 M	DECREASED COST > 10% ESTIMATED	
- Spares	1.662 M		
- Total	14.363 M		

TABLE 4. SYSTEMS ASSESSMENT SUMMARY
(ALL VALUES EXPRESSED IN TERMS OF EFFECT ON CH-47C PARAMETERS)

EFFECT ON	PREDICTED UNDER CONTRACT DAAJ02-74-C-0052	REVISED ASSESSMENT	CHANGE IN ASSESSMENT
RELIABILITY			
- Maintenance Rate/Flight Hour	+0.0021307	+0.0041920	+.0020613
- Mission Rate Change for 1-Hour Mission	+0.000415675	+0.000918	+.0005023
- Flight-Safety Rate Change for 1-Hour Mission	-0.0000015324	NEG.	NEG.
MAINTAINABILITY			
- Scheduled MMH/1000 FH	+1.812	+3.769	+1.957
- Unscheduled MMH/1000 FH	+1.437	+4.046	+2.609
- Total MMH/1000 FH	+3.249	+7.815	+4.566
AVAILABILITY			
- Unscheduled Maintenance	-0.1707%	-0.3470%	- .176%
- Scheduled Maintenance	-0.12756%	-0.3813%	- .254%
- Total	-0.29826%	-0.7283%	-0.430%
PERFORMANCE			
- Payload Change	+109-lb	+128	+19
- Range	+ 5.4 mm	+ 5.7 mm	+ 0.3 mm
- Speed	NO CHANGE	NO CHANGE	NO CHANGE
- Agility	+ 21.8 fpm	+ 24.6 fpm	+ 1.8 fpm
- Fuel Flow Rate	- 2.7 lb/hr	- 3.0 lb/hr	- 0.3 lb/hr
WEIGHT	-109 lb	-128 lb	-19 lb
COST			
- RDT&E	1.625 M	1.925 M	+ 0.3 M
- 250 Kits	11.076 M	DECREASED COST > 10% ESTIMATED	
- Spares	1.662 M		
- Total	14.363 M		

AVAILABILITY

The impact on operational availability is more difficult to assess. Many variables enter into the computations influencing operational availability such as flight profile, mission requirements, local-command operational and maintenance procedures, pilot judgments, etc., so that a realistic value is hard to determine. However, this analysis does accurately portray the trend the changes would effect. The operational-availability value in this analysis is measured in percentage of time the aircraft is available and represents only the amount of increased or decreased maintenance downtime caused by incorporation of the changes.

WEIGHT

Weight delta for the revised assessment was calculated as follows:

	ITEM	CHANGE
1.	FBW Backup System Instl.	+ 70
2.	Delete Existing Closet Armor	-246
3.	Add Armor (7.62mm threat level) Protection for Lower Boost Actuators	+ 48
	NET CHANGE	-128

COST

Revised cost estimates were based on cost figured under Contract DAAJ02-74-C-0052 factored to reflect rate changes and new vendor cost information based on the system as developed under the current contract. The figures represent planning costs and have not been worked through the normal estimating procedure at Boeing.

CONCLUSIONS

The feasibility of a fly-by-wire linkage operating as a backup to the existing CH-47C Flight Control System was successfully demonstrated.

A low gain actuator differential pressure feedback and mechanical system compliance will be used to compensate for tracking errors between the systems. The backup system does not require any pilot action in obtaining open failure protection, nor does it require any clutches for disengagement. This is desirable, since it avoids compromising mechanical system integrity.

Testing showed that mechanical system performance was not degraded, and in some instances was actually enhanced by the fly-by-wire backup. Conservative failure mode testing indicates that aircraft transients subsequent to control system failure are predicted to be within MIL-H-8501A limits. In most cases, indefinite time delays are anticipated. The testing did reveal the advisability of dualizing the longitudinal axes in the fly-by-wire to minimize failure transients.

In addition, testing showed the desirability of incorporating an automatic shutdown subsequent to passive fly-by-wire actuator failure to minimize any handling quality degradation. The program defined a potential production configuration which can form the basis for life cycle cost assessment.

RECOMMENDATIONS

It is recommended that:

1. The life cycle cost of the fly-by-wire backup system be assessed.

2. Assuming a favorable life-cycle cost assessment, a follow-on program to develop and flight-evaluate a production prototype be considered.

3. Anti-jam devices be included with the fly-by-wire backup to reduce the potential for broken controls resulting in a jammed system.

APPENDIX A
CH-47C FBW FEASIBILITY TEST OUTLINE

ABSTRACT

This test outline is submitted in fulfillment of Contract DAAJ02-75-C-0052, Paragraph F.1.a.6.

The objectives of this program are to conduct laboratory tests, evaluation and analysis, to determine the feasibility of utilizing an electrical linkage as a backup to the existing mechanical control system on the CH-47C helicopter.

The modified 347 mechanical flight control system installed on the "iron bird" will be used for testing. A single channel of the 347 ATC program Fly-By-Wire System will be used as the electrical linkage.

INTRODUCTION

The objective of this test outline is to define the tests required to:

(1) Determine the operational characteristics of the mechanical system for use as a baseline (fly-by-wire backup disconnected at SDA).

(2) Determine the performance characteristics of the flight control system, with the FBW backup connected, using the electrical system slaved to the mechanical system and vice versa.

(3) Determine the performance of the system for open mechanical linkage before and after the mix, and for passive and hardover failures of the FBW backup system.

(4) Determine the effects of depressurizing and bypassing lower boost actuators on normal mechanical FCS operations and on mechanical FCS with FBW failed.

TEST OUTLINE

I. Mechanical System Checkout

A. Balance cockpit controls (mechanical controls to lower boost, per D347-10095-1).

B. Check looseness and/or binding.

1. Disconnect each boost input.
Disconnect each swashplate drive actuator (SDA).
Disconnect each axis at stick boost output in turn.

a. Check system for excessive friction, looseness, or binding. Isolate source by disconnecting linkages as required, then correct problem.

<u>NOTE:</u> Friction at lower boost output should not exceed 10-lb.

2. Check friction of SDAs.

<u>NOTE:</u> Should not exceed 20-lb.

C. Conduct quantitative check of cockpit force feel.

1. Identify and eliminate source of friction if force feel is not acceptable.

2. Check proper operation of magnetic brakes.

II. <u>Stability Augmentation System Checkout</u>

A. Check for normal response to test switch inputs and signal inputs.

B. Check and verify proper response to external pitch and yaw inputs.

C. Check interface into Direct Electrical Linkage Control Unit (DELCU).

D. Check proper response to hydraulic shut-off valve operation.

III. <u>Electrical Link Functional Checkout</u>

A. Engage electrical system and check system response to:

1. Built-in-test (BIT inputs)

2. Delta P Feedback

3. Reset

4. Pilot and SAS Inputs

B. Adjust mechanical stops to be within electrical limits.

C. Check tracking of mechanical and electrical link with SDA disconnected. Change SDA electrical null to correct for any mistract.

D. Run baseline static (X-Y plots) and dynamic frequency response tests to verify the relationship of selected input control position to its related actuator output positions. Record the following data:

1. SPT inputs to DELCU

2. SDA piston position

3. Upper Boost Actuator (UBA) position

IV. <u>Electrical/Mechanical Performance Evaluation</u>

A. With SDA connected and delta P switch in "OUT" position, make an X-Y plot of input vs. output, and input vs. delta P.

NOTE: Delta P should stay within ±150 psi (i.e., no force fight comparitor trip).

1. Readjust null if necessary to keep force fight comparitor from tripping.

2. Evaluate performance comparison in relation to baseline data for improvements in input/output characteristics.

B. With Delta P F/B "IN", evaluate system static performance:

1. With circuit card P/N 292G333G2 S/N 72L0008 installed in forward right position, evaluate static performance with various delta P gains and shaping.

2. With delta P F/B "IN", adjust gain and shaping to achieve the best static and dynamic characteristics.

a. Evaluate system performance with a mechanical open.

b. To check for dead band effects, evaluate system performance with delta P F/B "IN" vs. delta P F/B "OUT".

C. Evaluate to determine the best system configuration of IV.A. and IV.B. above, for the following failure. conditions:

<u>NOTE:</u> Failures transients shall not exceed MIL-H-8501 limits.

1. Failure Conditions

a. Hardover

b. Driver go dead

c. Open mechanical system before the mixer.

d. Open mechanical system after the mixer.

NOTE: Plot static performance with the failures in and with the SDA shut down.

2. Evaluate desirability of automatic shutdown as compared with manual shutdown.

3. Evaluate ability of the force fight monitor to detect each type of actuator failure.

D. Depressurize stick boost actuators and evaluate ability to control upper boost for:

1. Normal conditions

2. Driver go dead

3. Open mechanical system before the mixer.

4. Open mechanical system after the mixer.

5. Driver hardover.

6. Evaluate system stability and static performance using pilot and SAS inputs. Evaluate impact of SAS feedback to the pilot's controls.

E. Select the most desirable system configuration based on the previous tests and record final data, showing:

1. Static and Dynamic Performance

a. Electrical link "ON"

b. Electrical link "OFF"

2. Response to failures

F. Conduct Boeing Vertol and Customer demonstration of the final configuration.

APPENDIX B

GENERAL ELECTRIC DATA

REV A
VEM NO. CH 47 GE-01
DATE 19 September 197

BOEING - GENERAL ELECTRIC HLHS FCS
VENDOR ENGINEERING MEMORANDUM (VEM)

In reply refer to
VEM No. & subject.

To: The Boeing Company
Vertol Division
Box 16858
Philadelphia, Pa. 19142

Attention: R. L. Powell

Subject: MODIFICATIONS TO DELS EQUIPMENT FOR CH 47 FLY-BY-WIRE BACKUP DEMONSTRATION

Reference: EWR dated 8/27/75

The Engineering Work Request has been reviewed and the modification instructions included have been prepared. Please review these instructions and direct comments to the author as soon as possible in order to expedite the completion of the modifications.

The mechanization shown in figure 1 of the BITE tests (item II.3 of the EWR) differs from that indicated in the EWR. This mechanization requires that the BITE #2 module be modified rather than the BITE #1 there is no space on BITE #1 for the added relay, therefore a spare BITE #2 board will have to be provided to GE for modification. In this mechanization, the original DELS BITE circuits are never energized; i.e., BITE is never armed, if desired the +28 V used to excite relay K1 could be interrupted by the THROTTLE STOP switch. (Not desired by B/V.)

REV A Boeing/Vertol has reviewed, and changes requested have been incorporated.

Prepared by: W. E. Chace WEC Reviewed by: D. Hogan D.H.

VEM affects (check)		Action Required	
☐ Delivery	☐ Specification	☐ Safety	☐ Ground Support Equip.
☐ Spares	☐ Reliability	☐ Installation	☐ Operating Procedures
☐ Weight	☐ Performance	☐ Publications	☐ Overhaul Methods
☐ Cost	☐ Test	☐ Maintainability	☐ Interchangeability

NOTE: This VEM does not provide for any change in contractual requirements. Any change that may result from this VEM is subject to agreement between Boeing Purchasing and G.E. Marketing prior to initiation of a contractual change.

Successful completion of the delta P LVDT test will be indicated on the Failure/Status panel by the presence of all four actuator location failure LEDS and the delta PRESS LVDT LED. Successful completion of the FORCE FIGHT test will be indicated by the presence of all four actuator location failure LEDS and the FORCE FIGHT (formerly MIXER) LED on the Failure/Status panel. J4 pins 31 and 32 have been selected by GE, please indicate your concurrence. (B/V concurs.)

VEM NO. CH-47 GE-01 REV A

MODIFICATION TO DEL CONTROL UNIT -- GE P/N 292E325G2
SN 73003
FOR FLY-BY-WIRE BACKUP DEMONSTRATION

REV A

I. DELETE THE FOLLOWING RUNS OR PORTIONS OF RUNS:

1. A7-37 A12-38 A12-40
2. A7-40 A12-36 A12-39
3. A6-37 A13-38 A13-40
4. A6-40 A13-36 A13-39
5. A5-37 A14-38 A14-40
6. A5-40 A14-36 A14-39
7. A4-37 A15-38 A15-40
8. A4-40 A15-36 A15-39

DELETE CIRCLED CONNECTION

9. A2-44 A2-13 A17-13 J1-25
10. A16-40 A18-9
11. A3-40 A1-9
12. A17-40 A17-14 A2-14 J1-31
13. A3-54 A1-11
14. A16-54 A18-11
15. A16-44 A10-92
16. A3-44 A10-41
17. A10-27 A12-26 A13-26 A14-26 A15-26

II. ADD THE FOLLOWING RUNS:

1. A2-44 A3-40 A16-40, J1-25
2. A17-44 A16-54 A3-54, J1-31
3. A12-10 A12-39
4. A13-10 A13-39
5. A14-10 A14-39
6. A15-10 A15-39
7. A12-38 A13-38 A14-38 A15-38 J5-38 A10-30
8. J5-39 J1-3 (28 red)
9. ~~J5-40 J2-11 (28 blk)~~ deleted
10. A19-35 J4-39 J4-41 J4-43 J4-49
11. J4-38 J6-6
12. J4-40 J7-6
13. J4-42 J8-53
14. J4-48 J8-44
15. J4-31 E2 (28 blk)
16. J4-32 A10-4
17. A10-59 A11-59 (28 red)
18. A10-95 A12-7
19. A10-96 A13-7
20. A10-97 A14-7
21. A10-98 A15-7
22. A12-26 A12-51
23. A13-26 A13-51
24. A14-26 A14-51
25. A15-26 A15-51

MODIFICATIONS TO CIRCUIT MODULES FOR FLY-BY-WIRE BACK UP DEMONSTRATION

I. MODULE: ACTIVE SERVO LOOP

PN 292E333G2
SN 72L0008, 9, 10, 11, 12

REV A 1. Deleted

2. Delete the following:
   CR14
   R62
   R61
   E4-E5 jumper
   E11-E12 jumper
   Q7

3. Add jumpers U3-1, U3-2, U3-5, U3-6; U2-14 to U2-1; Q7E to Q7C
4. Add resistor R128 on terminals, 130 K.

5. Add potentiometer R129, 5K
   connect red lead to R128
   connect green lead to +12V
   connect yellow lead to -12V

ON SN 72L0008 ONLY:

6. Delete R10, R119, C1, C2
   add terminals EX1, connect to R9
   EX2, connect to R21
   EX3, connect to gnd
7. Change R21 from 200K to 10K

II. MODULE: MODEL SERVO LOOP

PN 292E334G2
SN 72L0008, 9, 10, 11, 12

1. Change R55 and R56 from 49.9 K to 20.5 K
2. Delete Q7
3. Add jumper Q7-E to Q7-C.

III. MODULE:STICK MIXER

PN 292E332G2
SN 72L0004, 5, 6

REV A

1. Change R44 from 80.6 K to 121 K
2. Change R140 from 64.9 K to 97.6 K
3. Add connection U1-13 to U1-7.

IV. MODULE:BITE #2

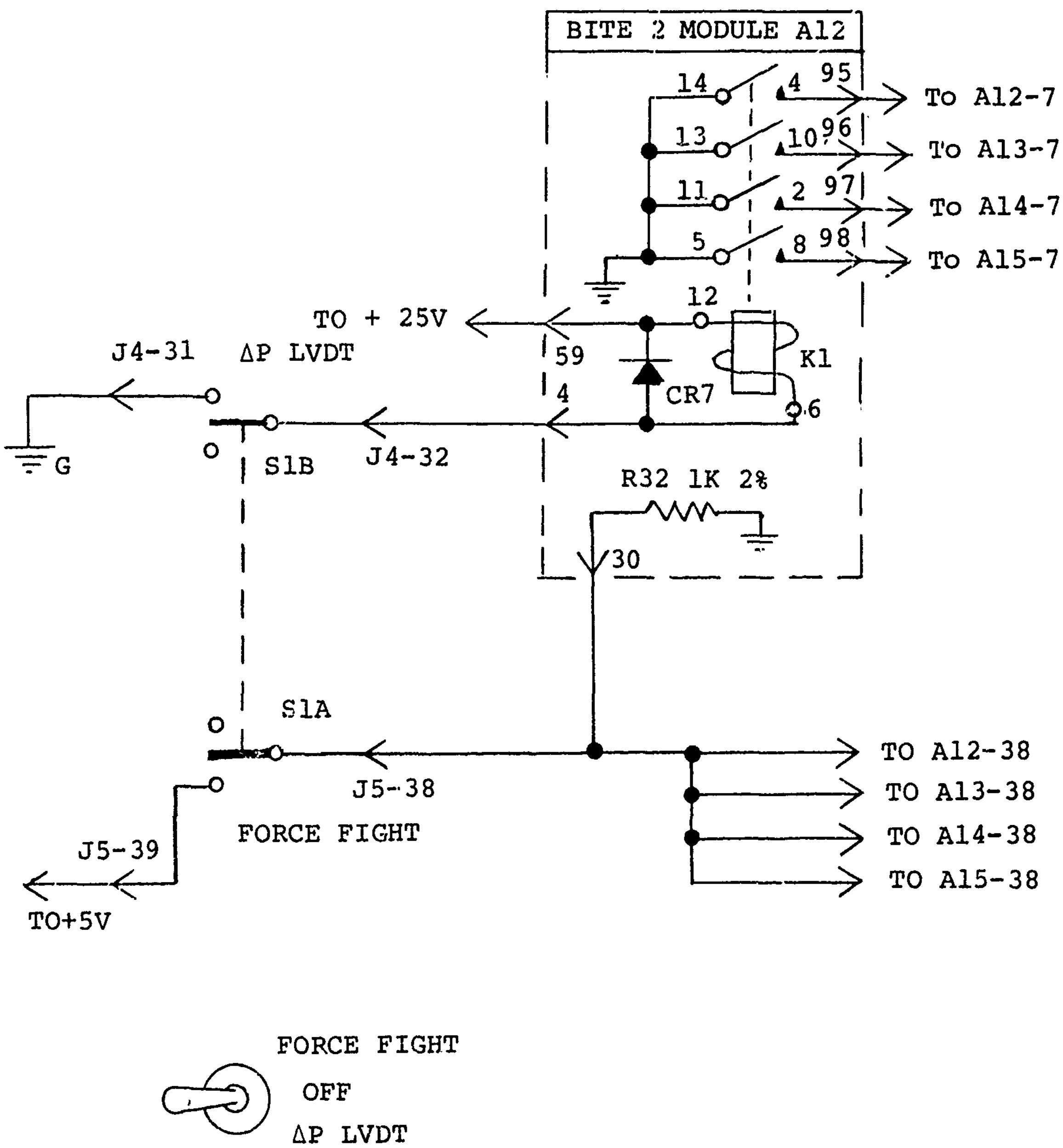
PN 292E335G2
SN 72L0003, 4

1. Add relay K1, M5757/80-018
2. Add diode CR14, JAN1N645, on terminals of K1.
3. Connect K1 as shown on figure 1.
4. Add resistor, R32, connect to P1-30 and gnd.

V. MODULE:RELAY

PN 113D8668G1
SN 72L0003, 4

1. Add the following jumpers:
   K2-3 to K2-6
   K4-3 to K4-6
   K6-3 to K6-6
   K8-3 to K8-6



SI-BITE SWITCH - DPDT C OFF, SPRING LOADED TO CENTER POSITION

FIGURE B-1. CONNECTION DIAGRAM FBW BACKUP BITE

VEM NO. CH 47 GE-02
DATE 14 October 1975

BOEING - GENERAL ELECTRIC HLHS FCS
VENDOR ENGINEERING MEMORANDUM (VEM)

In reply refer to
VEM No. & subject.

To: The Boeing Company
Vertol Division
Box 16858
Philadelphia, Pa. 19142

Attention: R. L. Powell

Subject: CH 47 FBW BACKUP MODIFICATION TESTS

Reference: EWR dated 8/27/75

The following checks and tests on the modified control unit and circuit boards have been performed successfully.

Wiring Checks

1. Wire check frame wiring mods for proper deletions and additions per VEM No. CH 47 GE-01 Rev A.

2. Visual inspection and wire check of modified circuit boards for proper modification and workmanship.

Electrical Tests

I. ΔP Bias Pots

1. With the ΔP input signal at null, set the bias pots fully CW and measure VDC at ΔP test points J1-35, 39, 43, 47.

Limits: +1.754/+1.938
(+1.846 ±5%)

DH

Prepared by: W. E. Chacé WEC. Reviewed by: D. Hogan

VEM affects (check)		Action Required	
☐ Delivery	☐ Specification	☐ Safety	☐ Ground Support Equip.
☐ Spares	☐ Reliability	☐ Installation	☐ Operating Procedures
☐ Weight	☐ Performance	☐ Publications	☐ Overhaul Methods
☐ Cost	☒ Test	☐ Maintainability	☐ Interchangeability

NOTE: This VEM does not provide for any change in contractual requirements. Any change that may result from this VEM is subject to agreement between Boeing Purchasing and G.E. Marketing prior to initiation

2. Set the ΔP bias pots fully CCW and repeat the above measurements.

   Limits: -1.754/-1.938
   (-1.846 ±5%)

3. Set the ΔP bias pots to null the DC voltage at the ΔP test points.

DATA

Bd. S/N	ACT. LOC	Test Point	CW	CCW
9	FR	J1-35	+1.816	-1.843
10	FL	J1-39	+1.829	-1.832
11	AR	J1-43	+1.841	-1.822
12	AL	J1-47	+1.853	-1.804
8	Spare		+1.846	-1.815

II. Failure Detection Inhibits

Cause the following conditions to occur one at a time, none of the conditions shall cause an actuator failure or an actuator location LED on the Failure/Status panel.

1. SPT input command difference > 10%, each of 4 axes.
2. Spool position vs current comparator hardover, each of 4 actuators.
3. Active current vs model current comparator hardover, each of 4 actuators.
4. Actuator position LVDT secondary open, each of 4 actuators.
5. Actuator postion LVDT secondary short to LVDT excitation, each of 4 actuators.

III. ΔP Force Fight Detector Tests

Vary the ΔP input pot in the EXTEND and RETRACT directions while monitoring the mixer LED and the selected ACTUATOR LOCATION LED on the failure/status panel. Record the ΔP AC input voltage which causes the leds to illuminate.

Limits: 0.937 VRMS ±5% = 0.890/0.983

DATA

Bd. S/N	Actuator Location	Extend	Retract
9	FR	0.947	0.917
10	FL	0.950	0.911
11	AR	0.946	0.918
12	AL	0.944	0.918
8	Spare	0.947	0.922

IV. Gain -- AFCS Input to Long and Direct LMTD Output

1. Longitudinal

Apply ±10 VDC to LONG A AFCS buffer, measure outputs at LMTD LONG test points J1-16 and J1-80. Calculate gain.

Gain Limits: -0.2102 ±2% = -0.206/-0.2144

DATA

Bd. S/N	Long Input	J1-16 Output	J1-80 Output	J1-16 Gain	J1-80 Gain
5 & 6	-9.937 +9.961	+2.129 -2.062	+2.128 -2.049	-0.2106	-0.2099
4	-9.932 +9.963	+2.137 -2.050		-0.2105	

2. Direct

Apply ±10 VDC to DIRECT A AFCS buffer, measure outputs at LMTD DIRECT test points J1-18 and J1-82. Calculate gain.

Gain Limits: -0.1957 ±2% = -0.1918/-0.1996

DATA

Bd. S/N	Direct Input	J1-18 Output	J1-82 Output	J1-18 Gain	J1-80 Gain
5 & 6	-9.940 +9.961	+1.985 -1.903	+1.985 -1.896	-0.1954	-0.1950
4	-9.941 +9.958	+1.982 -1.907		-0.1954	

V. BITE Tests

NOTE: These tests were performed twice, once with S/N 3 Relay and BITE #2 modules and once with the spare relay and BITE #2 modules.

1. Set up test bench in normal condition with no failures. Apply ground to J4-32. Note that the ΔP LVDT and all four actuator location leds illuminate on the Failure/Status panel and that channel "1 FAIL" lamp on the Pilot Status panel illuminates. Remove ground from J4-32, reset the F/S panel, all leds go OUT.

2. Apply +5 VDC to J5-38, note that the MIXER led and all four actuator location leds illuminate, and that the channel "1 FAIL" lamp on the Pilot Status panel illuminates. Rotate the actuator select switch through the four locations while noting that the shutoff valve "1" lamp is on and the "2" lamp is OFF in each location.

   At each location jumper the J4 connector pins specified and note that the "2" lamp illuminates while the jumper connection is made.

AFT LEFT	J4-48 to J4-49
FWD LEFT	J4-40 to J4-41
FWD RT	J4-38 to J4-39
AFT RT	J4-42 to J4-43

   Remove +5V from J5-38, reset F/S panel, all leds go OUT.

APPENDIX C
CH-47C FWB TEST METHODS

This section describes the methods used to obtain static, dynamic and time history data. A list of instrumentation parameters and data on test equipment used is also given.

1. Test Setups

   A. Static Testing - Static tests are conducted to assess the system gains, linearity, and hysteresis under static conditions. (Figure C-1)

   Figure 19 is a typical static plot. The hysteresis is the primary factor used in this program to compare performance of the electrical and mechanical systems.

   Hysteresis is a measure of the system's capability to pass small signals. Plots are made at full control travel and small control displacements (10 x sensitivity) to show performance variations with stroke. The small signal response is the best measure of hysteresis effects on ability to stabilize the aircraft.

   Plots are made by moving the cockpit control slowly and plotting the upper boost or fly-by-wire driver actuator motion (Y axis) versus the control motion (X axis) using an X-Y plotter.

   Plots were made for normal condition and failure conditions as indicated in Figure C-1.

   B. Dynamic Testing - Dynamic tests are conducted to assess system response to sinusoidal inputs to the Stability Augmentation System (SAS). Performance is measured in terms of the frequency response of the system. Frequency response is measured in terms of amplitude ratio (expressed in decibels) and phase shift (expressed in degrees phase lead). Figure 23 is a typical frequency response plot. See Figure C-2 for the test setup.

   Amplitude ratio in decibels is defined as:

   $$20 \log (\text{Output}/\text{Input})$$

   Amplitude ratio is usually normalized by referencing 0-db to the expected gain, a 0-frequency. To plot the curves in this report, the DC gain was measured by putting a large amplitude low-frequency sine wave into the system and using the measured gain in db to normalize the data.

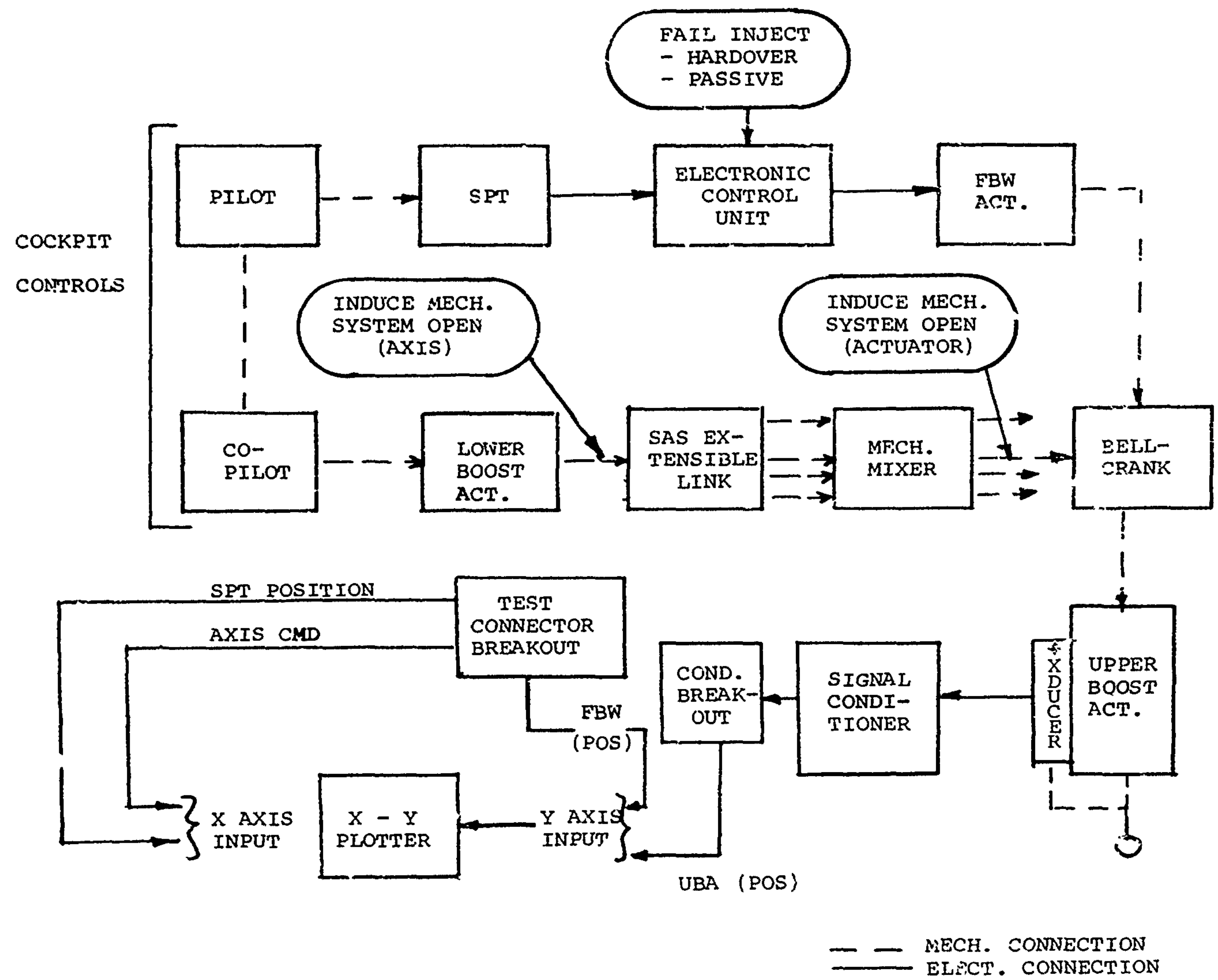


FIGURE C-1. SETUP FOR STATIC TESTING (INCLUDING FAILURES)

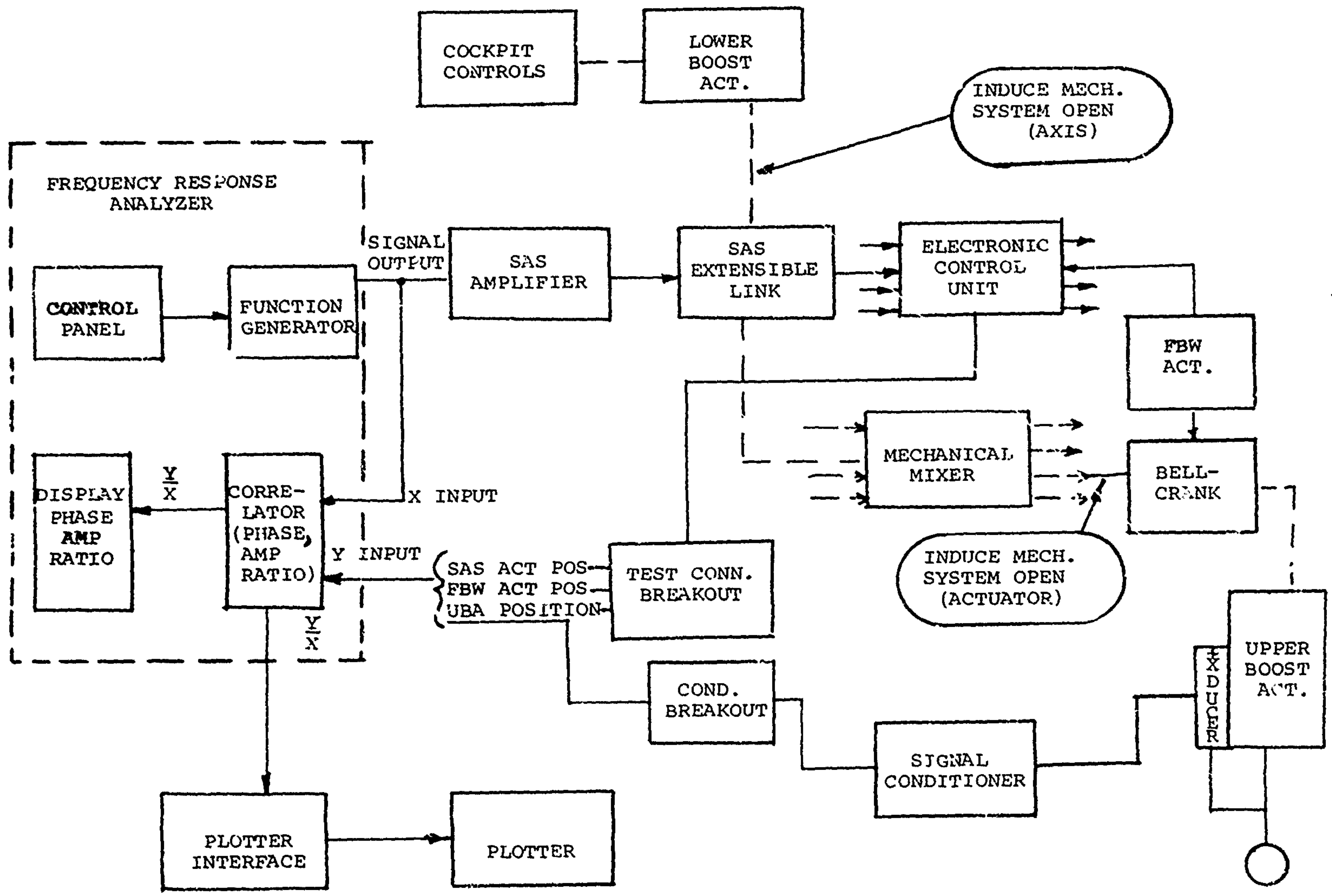


FIGURE C-2. SET-UP FOR DYNAMIC TESTING (Including Failures)

Phase lead is a measure of the delay between input and output. No delay would be 360 degrees phase lead.

The primary criterion used to measure performance in this report was phase lead at low frequency. This is a good indication of hysteresis or dead band effects in the system.

Amplitude ratio changes are also a measure of performance, but do not affect stability as much as phase shift.

For a linear system, amplitude ratio and phase shift are directly related; but since we have nonlinearities in the system (like friction), they are not always directly related.

Response was referenced to SAS input. Measurements were made at the SAS actuator motion transducer (FBW input), fly-by-wire driver motion transducer, and upper boost motion transducer. The contribution of each part of the system can be assessed by subtracting the gain and phase variation from its output to its input.

Performance was measured using a frequency response analyzer which directly calculates gain in db and displays phase shift in degrees. If desired, the results may be plotted directly on an X-Y plotter.

C. Time Histories - System response to pilot control motions was also recorded as a function of time on a strip chart recorder.

Figure C-3 shows the test setup. This method was used to show failure effects and differential pressure response to control motions.

Figure 30 is a typical time history response.

2. Instrumentation

Since the fly-by-wire system contains transducers for the measurement of position and differential pressure, the only external instrumentation required was that necessary to measure upper boost motion.

Instrumentation parameters and the associated gains are given in Table C-1. Table C-2 gives kinematics of the 347 control system.

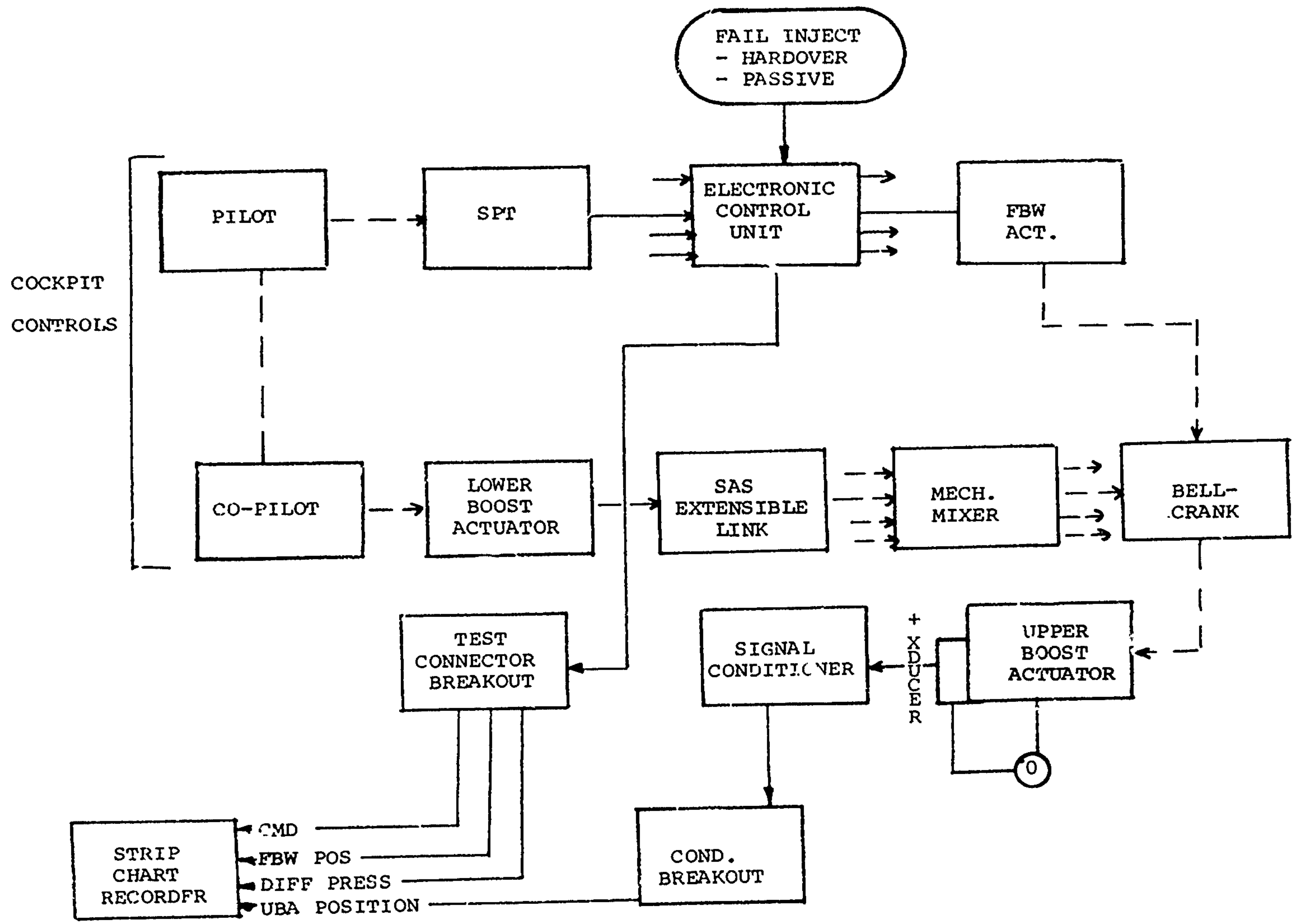


FIGURE C-3. SETUP FOR TIME HISTORIES

TABLE C-1. INSTRUMENTATION PARAMETERS

NOTES: 1 - AXIS POS IN. =
AXIS CMD IN. EQ
SAS CONTROL
2 - 3.7386 V/IN. SPT AT 26.8 VAC

	PARAMETER	OUTPUT POINT	OUTPUT GAIN[2]	NOMINAL RANGE	ACCURACY	REMARKS
1.	LONGITUDINAL POS.	TEST CONN TP10	1.241 IN./VOLT	±6.5 IN.	± 2%	MA 4.64
2.	LATERAL POS.	TEST CONN TP12	.813 IN./VOLT	5.01 IN. RT., 3.51 IN. LT.	± 2%	MA 3.04
3.	DIRECTIONAL POS.	TEST CONN TP13	.479 IN./VOLT	±2.5 IN.	± 2%	MA 1.79
4.	COLLECTIVE PITCH POS.	TEST CONN TP8	.918 IN./VOLT	±4.80 IN.	± 2%	MA 3.43
5.	LONG SAS INPUT	TEST CONN TP25	.309 IN./VOLT	± .80 IN.	± 2%	MA 4.75
6.	DIRECTIONAL SAS INPUT	TEST CONN TP28	.114 IN./VOLT	± .60 IN.	± 2%	MA 1.75
7.	LONG. AXIS CMD	TEST CONN TP16	1.237 IN./VOLT	±6.3 IN.	± 2%	MA 4.64
8.	LATERAL AXIS CMD	TEST CONN TP17	.957 IN./VOLT	4.99 IN. RT., 3.47 IN. LT.	± 2%	MA 3.04
9.	DIRECTIONAL AXIS CMD	TEST CONN TP18	.489 IN./VOLT	±2.49 IN.	± 2%	MA 1.79
10.	COLLECTIVE PITCH CMD	TEST CONN TP15	.938 IN./VOLT	±4.65 IN.	± 2%	MA 3.43
11.	FORWARD RIGHT FBW POS.	TEST CONN TP34	.624 IN./VOLT	±3.25 IN.	± 2%	MA .51
12.	FORWARD RIGHT FBW ΔP	TEST CONN TP35	28.33 LB/VOLT	±80 LB	± 2%	
13.	FORWARD LEFT FBW POS.	TEST CONN TP38	.624 IN./VOLT	±3.25 IN.	± 2%	MA .51
14.	FORWARD LEFT FBW ΔP	TEST CONN TP39	28.33 LB/VOLT	±80 LB	±10%	
15.	AFT RIGHT FBW POS.	TEST CONN TP42	.624 IN./VOLT	±3.25 IN.	± 2%	MA .518
16.	AFT RIGHT FBW ΔP	[illegible]	[illegible] LB/VOLT	±80 LB	±10%	
17.	AFT LEFT FBW POS.	[illegible]	[illegible] IN./VOLT	±3.25 IN.	± 2%	MA .518
18.	AFT LEFT FBW ΔP	[illegible] CONN TP47	28.33 [illegible]/VOLT	±80 LB	±10%	
19.	FORWARD RIGHT UBA POS.	SIG COND TP1	2.50 IN./VOLT	±6.25 IN.	± 4%	R_C 4.850
20.	FORWARD LEFT UBA POS.	SIG COND TP2	2.50 [illegible]/VOLT	±6.25 IN.	± 4%	R_C 3.188
21.	AFT RIGHT UBA POS.	SIG COND TP3	2.[illegible] IN./VOLT	±6.25 IN.	± 4%	R_C 3.318
22.	AFT LEFT UBA POS.	SIG COND TP4	2.[illegible] [illegible]/VOLT	±6.25 IN.	± 4%	R_C 4.820

TABLE C-2. MECHANICAL CONTROLS

BASIC ENGINEERING DATA MODEL HLH/347

AXIS OF CONTROL	COCKPIT CONTROLS SOURCE	COCKPIT CONTROLS MOTION IN.	M/A STICK TO STICK BOOST	STICK BOOST ACT. TRAVEL IN.	M/A STICK TO SPT (LVDT)	ROTOR HEAD	M/A SPT (LVDT) TO FBW ACT.	M/A STICK TO FBW ACT.	M/A STICK BOOST TO FBW ACT.	M/A DRIVER ACT. TO UPPER BOOST	FBW ACT. TRAVEL IN.	M/A STICK TO UPPER BOOST	UPPER BOOST TRAVEL IN.	M/A STICK BOOST TO UPPER BOOST	BLADE ANGLE TRAVEL DEG.	RATIO STICK TO BLADE ANGLE IN/DEG	RATIO BLADE ANGLE TO STICK DEG/IN
ROLL (LAT. CYCLIC)	LATERAL STICK	5.01 (R.H.) 3.51 (L.H.)	2.47	2.03 (UP) 1.42 (DN)	3.04	F	1.44	4.40	1.79	.51	1.14 .80	2.24	2.24R 1.57L	.915	11.15R 7.81L	.455	2.20
						A	1.47	4.48	1.83	.518	1.12 .78	2.32	2.16R 1.51L	.949	9.95R 6.97L	.505	1.99
YAW (DIFF. LAT. CYCLIC)	DIR. PEDALS	±2.50	1.75	±1.43	1.79	F	1.01	1.80	1.04	.51	±1.38	.92	±2.71	.529	±13.5	.186	5.38
						A	1.09	1.95	1.16	.518	±1.28	1.01	±2.48	.600	±11.6	.216	4.63
PITCH (DIFF. COLL.)	LONG. STICK	±6.50	4.75	±1.37	4.64	F	4.3	19.89	4.20	.51	± .33	10.12	± .64	2.14	±3.80	1.71	.585
						A	4.5	20.90	4.40	.518	± .31	10.83	± .60	2.28	±3.30	1.97	.508
THRUST (COLL. PITCH)	THRUST LEVER	9.60 (±4.80)	3.49	2.75 (±1.38)	3.43	F	1.57	5.41	1.53	.51	1.78 (±.89)	2.76	3.48 (±1.74)	.782	-0.8 to +19.8	.466	2.14
						A	1.69	5.75	1.65	.519	1.66 ±.83	2.98	3.22 (±1.61)	.855	-1.69 to +16.01	.541	1.85
CUMULATIVE LATERAL: COMBINED ROLL & YAW			RIGHT PEDAL RIGHT STICK			F							-3.57 R		17.8°		
			LEFT PEDAL LEFT STICK			F							-3.18 L		15.8°		
			RIGHT PEDAL LEFT STICK			A							-3.28 L		15.1°		
			LEFT PEDAL LEFT STICK			A							-3.60 R		16.6°		

Control position, axis command, and SAS actuator position have been converted to equivalent pilots grip motion.

Fly-by-wire parameters may be related to upper boost by the MA shown (i.e., upper boost motion is approximately twice fly-by-wire actuator motion).

Parameters contained within the fly-by-wire system are brought on the test connector and accessed through the preflight test set. Upper boost motions are measured using potentiometers, signal conditioned and accessed through a patch panel.

3. Test Equipment

Major items of test equipment used are listed below:

a. XY Plotter

Moseley Model 2D, S/N 340500

b. Frequency Response Analyzer

Schlumberger EMR1170

c. Frequency Response Analyzer Plotter Interface

Schlumberger Solartron 1180

d. Strip Chart Recorder (8 Channel)

Brush Instruments Mark 200

e. DC Nullmeter

Hewlett Packard 419A

f. AC Voltmeter

Hewlett Packard 400D

g. Scope

Tektronic 561A
Type 72 Dual Trace Amp.
Type 67 Time Base

h. Instrumentation Package

Boeing S/K 24918

APPENDIX D
ADDITIONAL DATA ON MECHANICAL SYSTEM
(FLY-BY-WIRE DISCONNECTED)

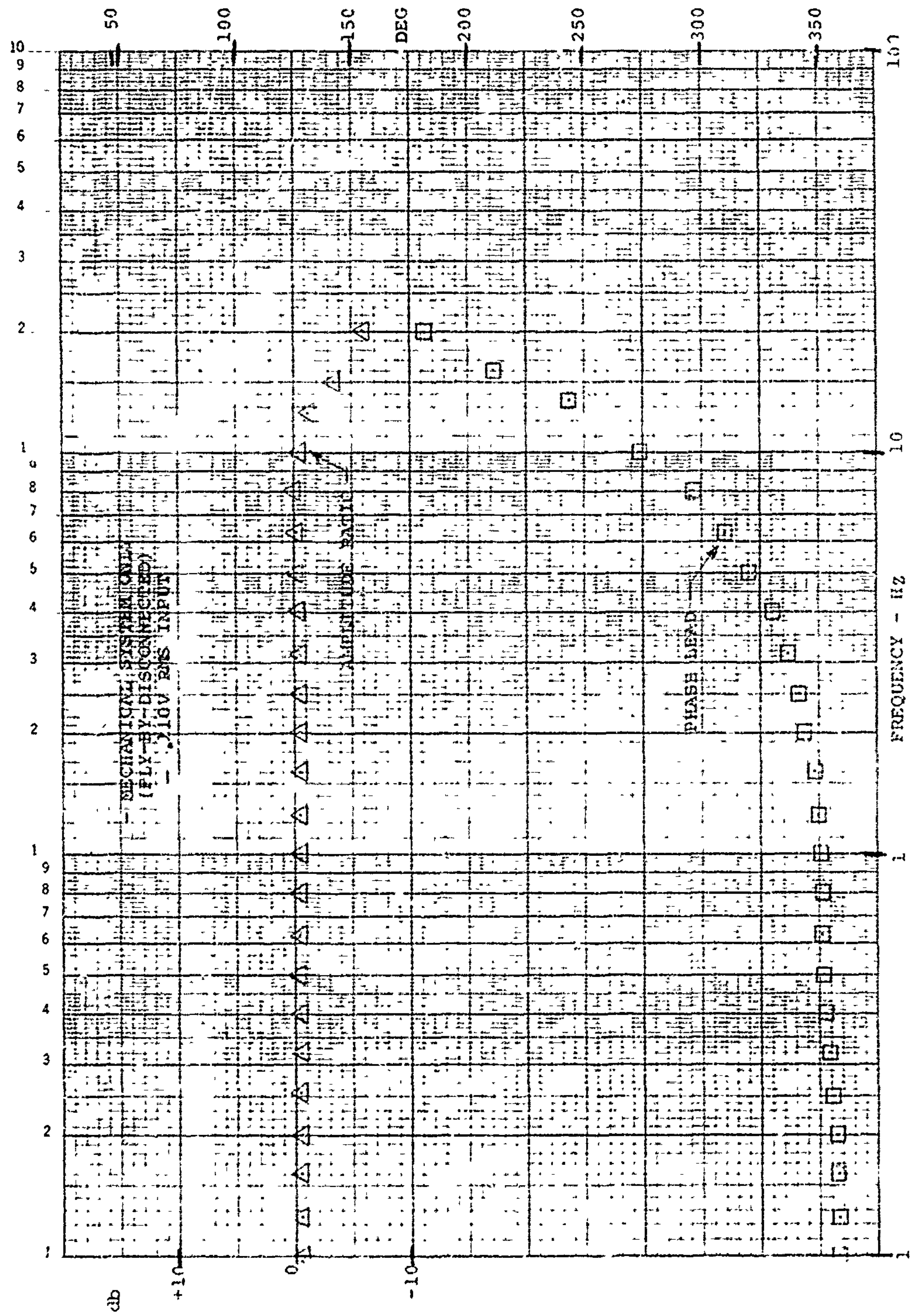


FIGURE D-1. LONGITUDINAL SAS ACTUATOR VS DIRECTIONAL SAS COMMAND

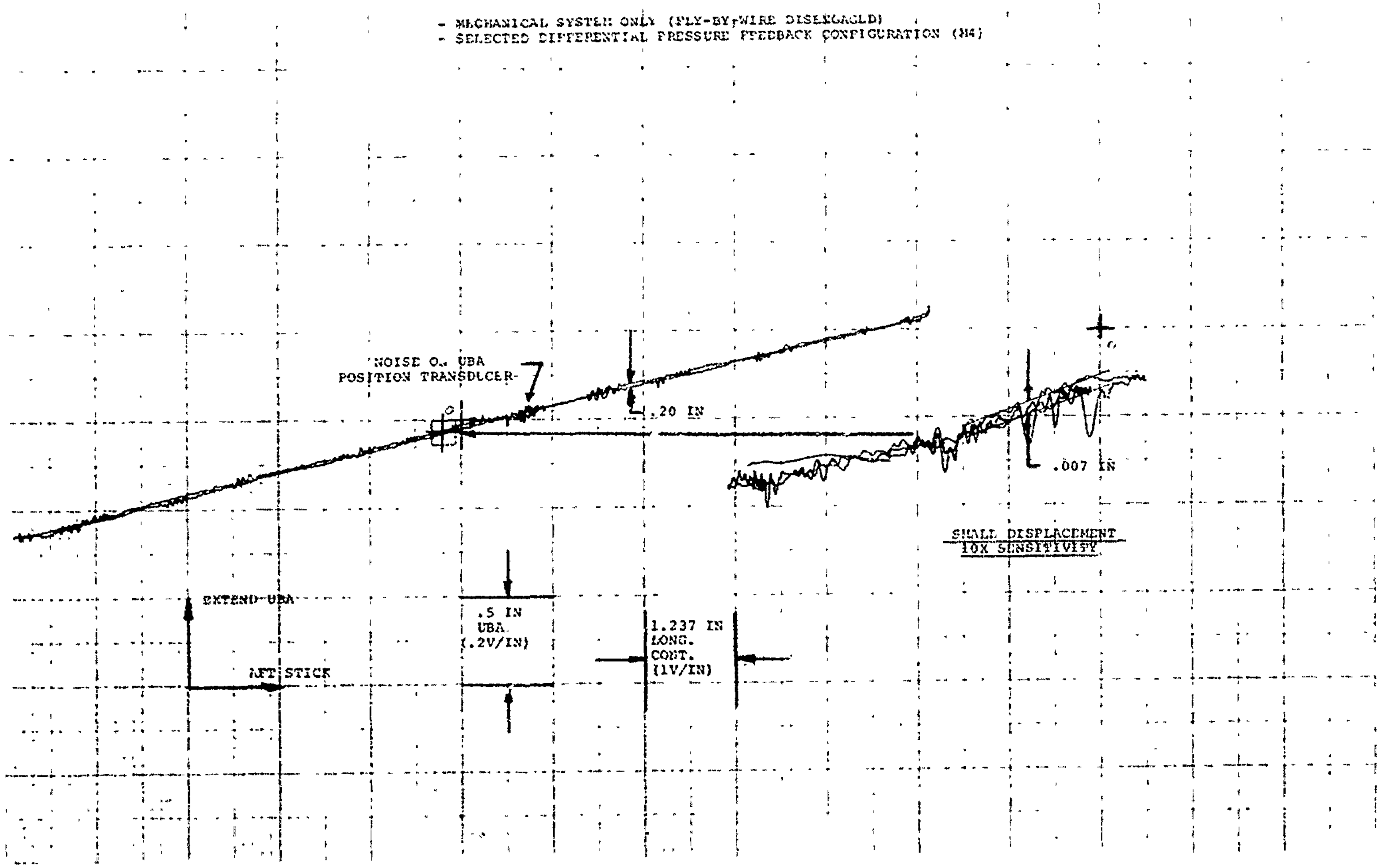


FIGURE D-2. FORWARD RIGHT UPPER BOOST ACTUATOR VS LONGITUDINAL AXIS DISPLACEMENT (TP-16)

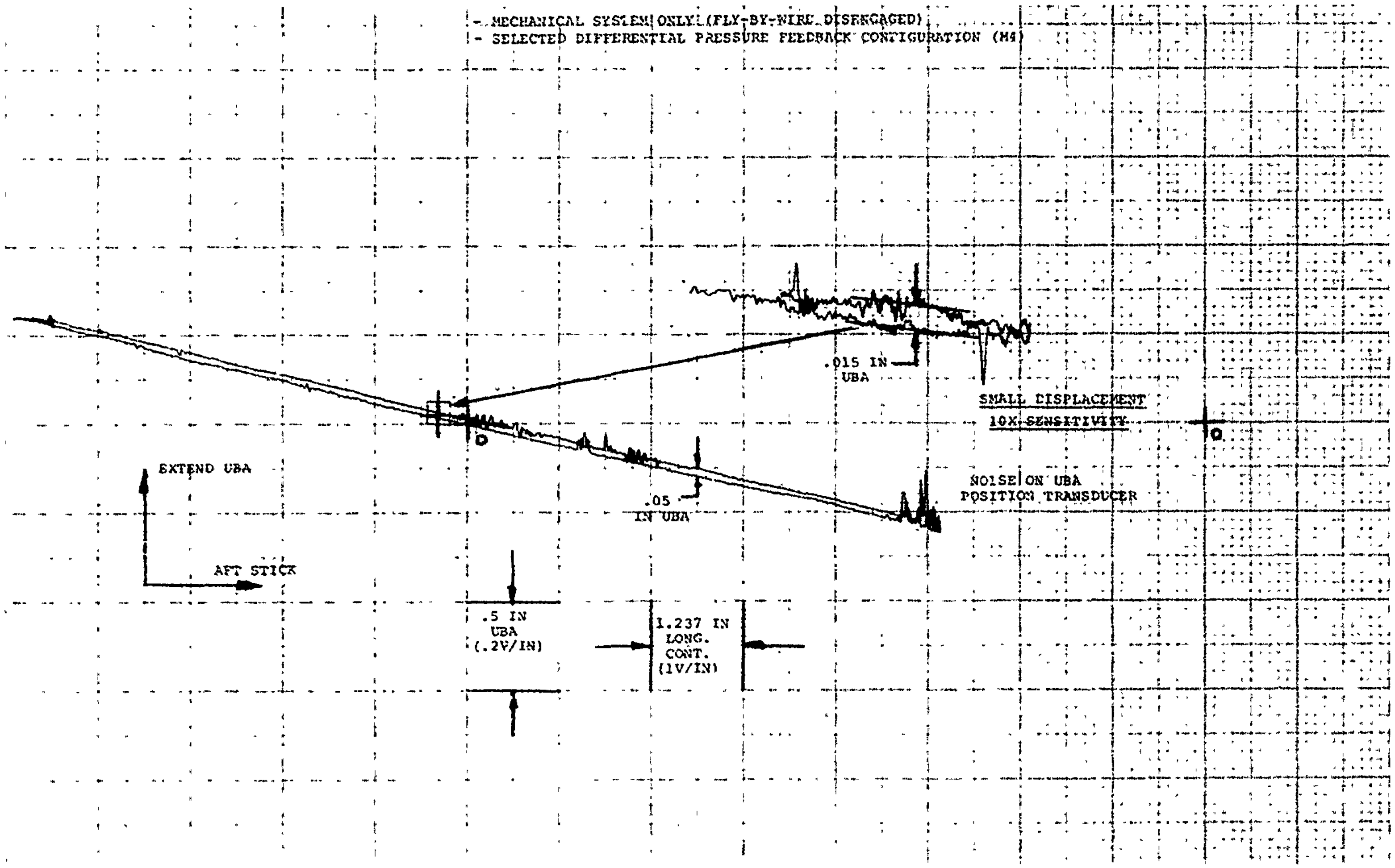


FIGURE D-3. AFT LEFT UPPER BOOST ACTUATOR VS LONGITUDINAL AXIS DISPLACEMENT (TP-16)

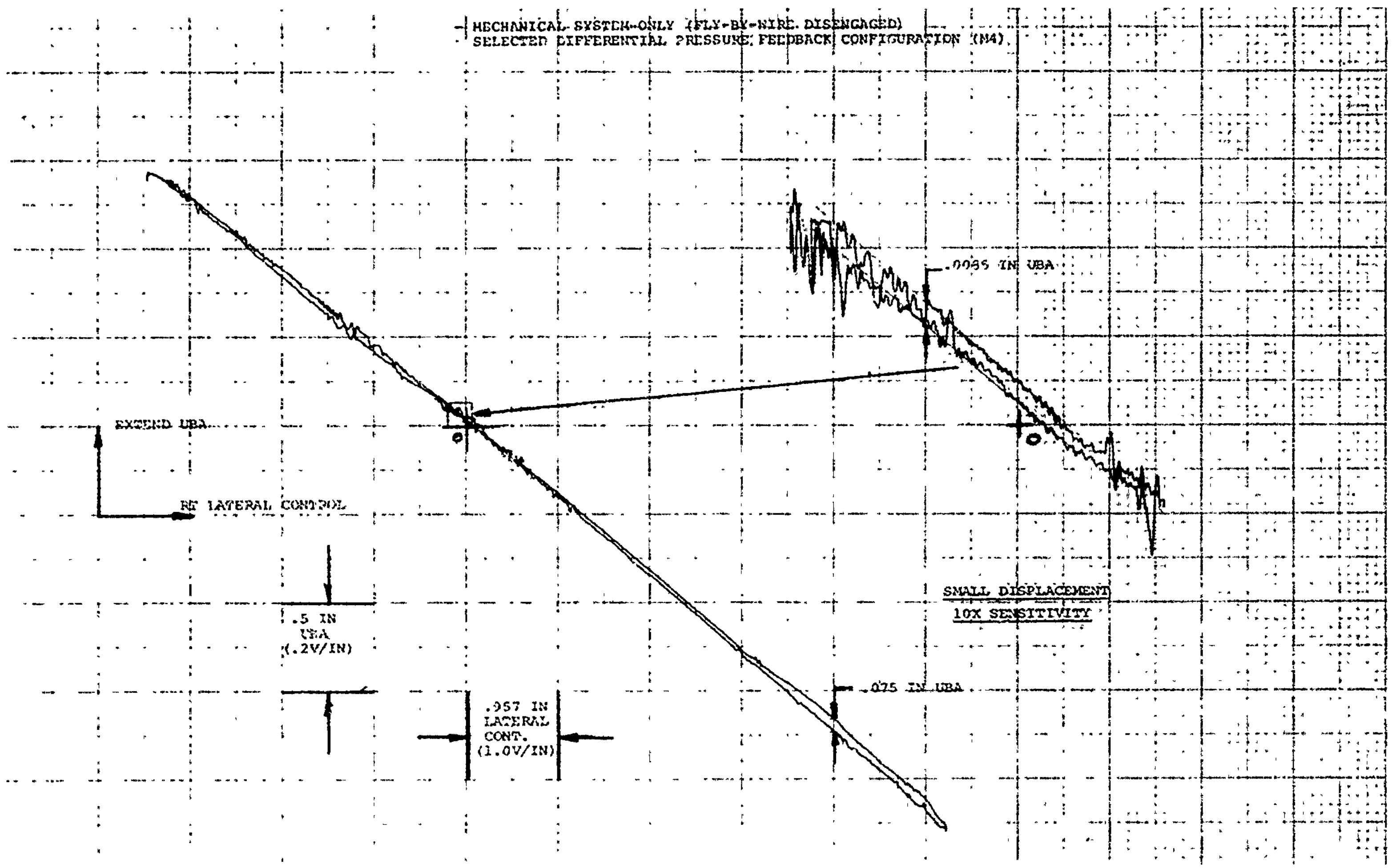


FIGURE D-4. FORWARD RIGHT UPPER BOOST ACTUATOR VS LATERAL AXIS DISPLACEMENT (TP 17)

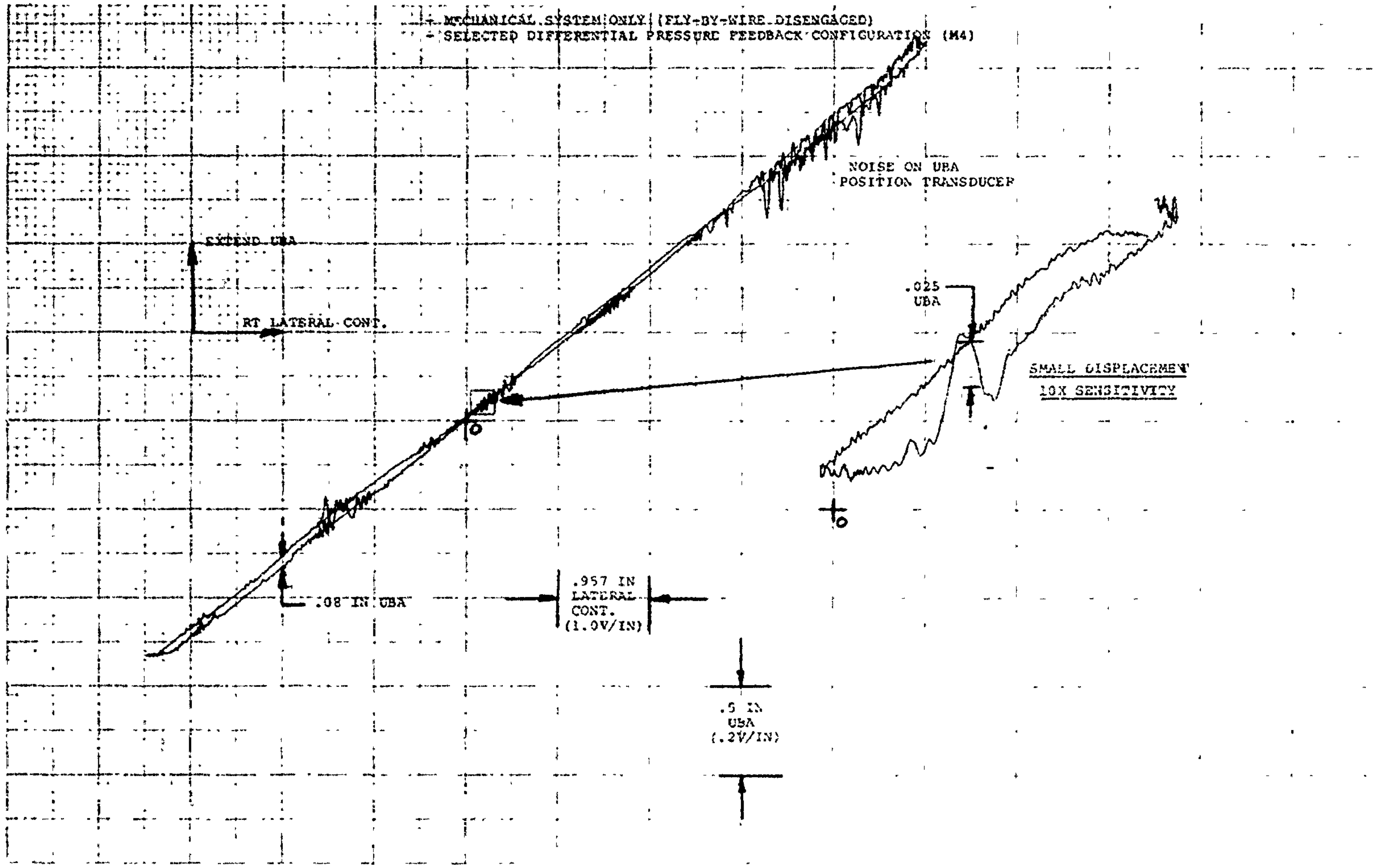


FIGURE D-5. AFT LEFT UPPER BOOST ACTUATOR VS LATERAL AXIS DISPLACEMENT (TP 17)

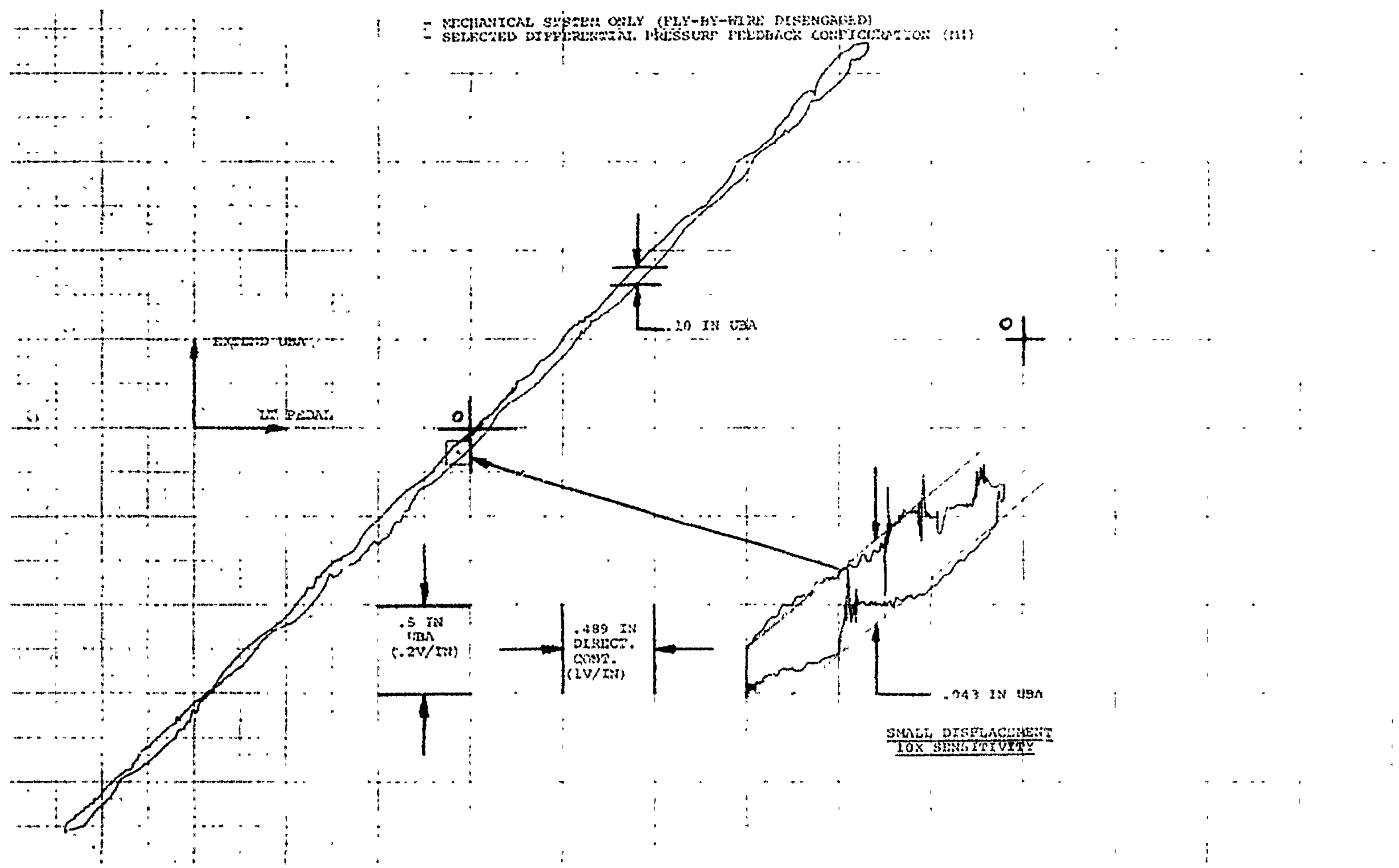


FIGURE D-6. FORWARD RIGHT UPPER BOOST ACTUATOR VS DIRECTIONAL AXIS DISPLACEMENT (TP 18)

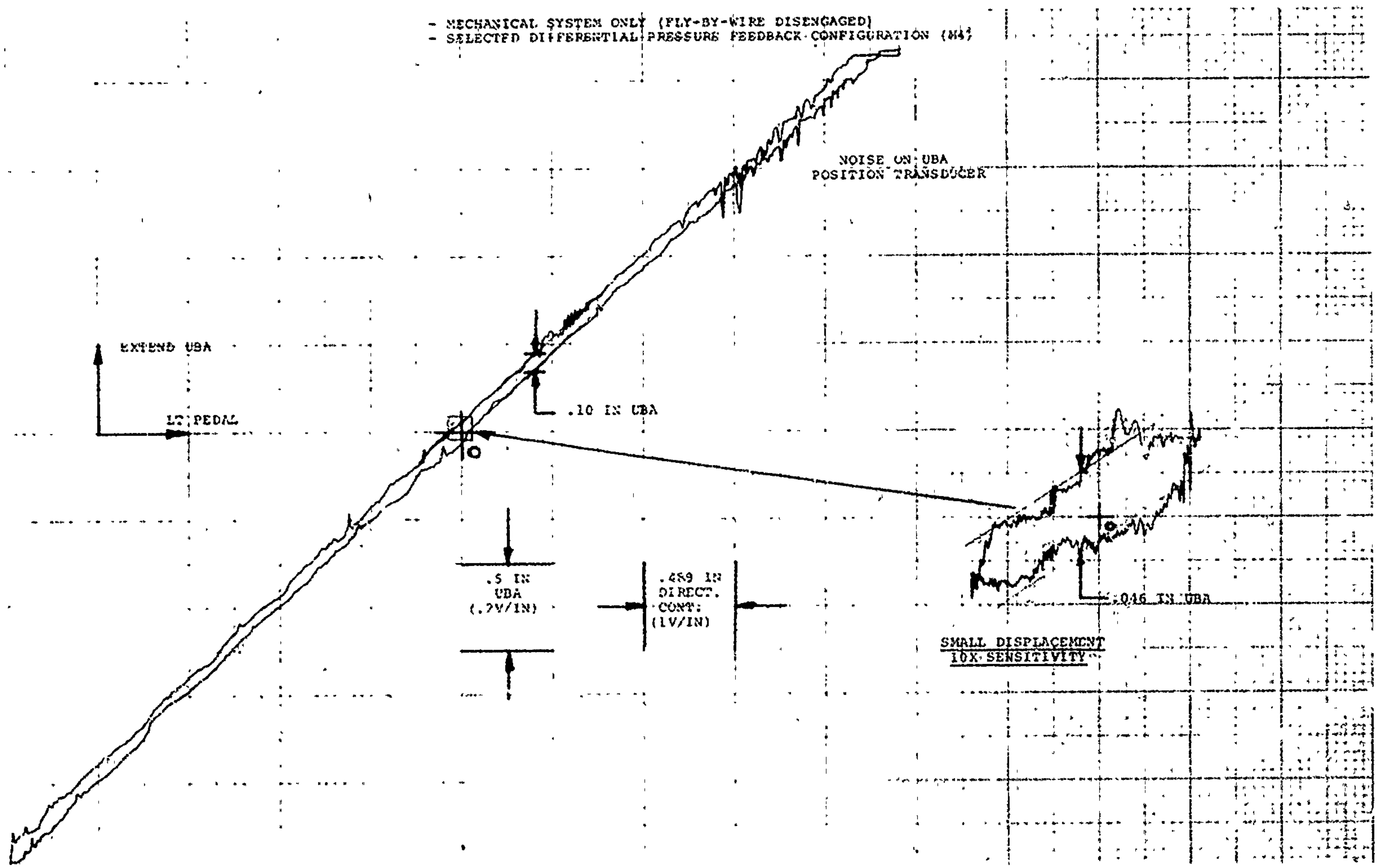


FIGURE D-7. AFT LEFT UPPER BOOST ACTUATOR VS DIRECTIONAL AXIS DISPLACEMENT (TP 18)

APPENDIX E
ADDITIONAL DATA ON SELECTED CONFIGURATION

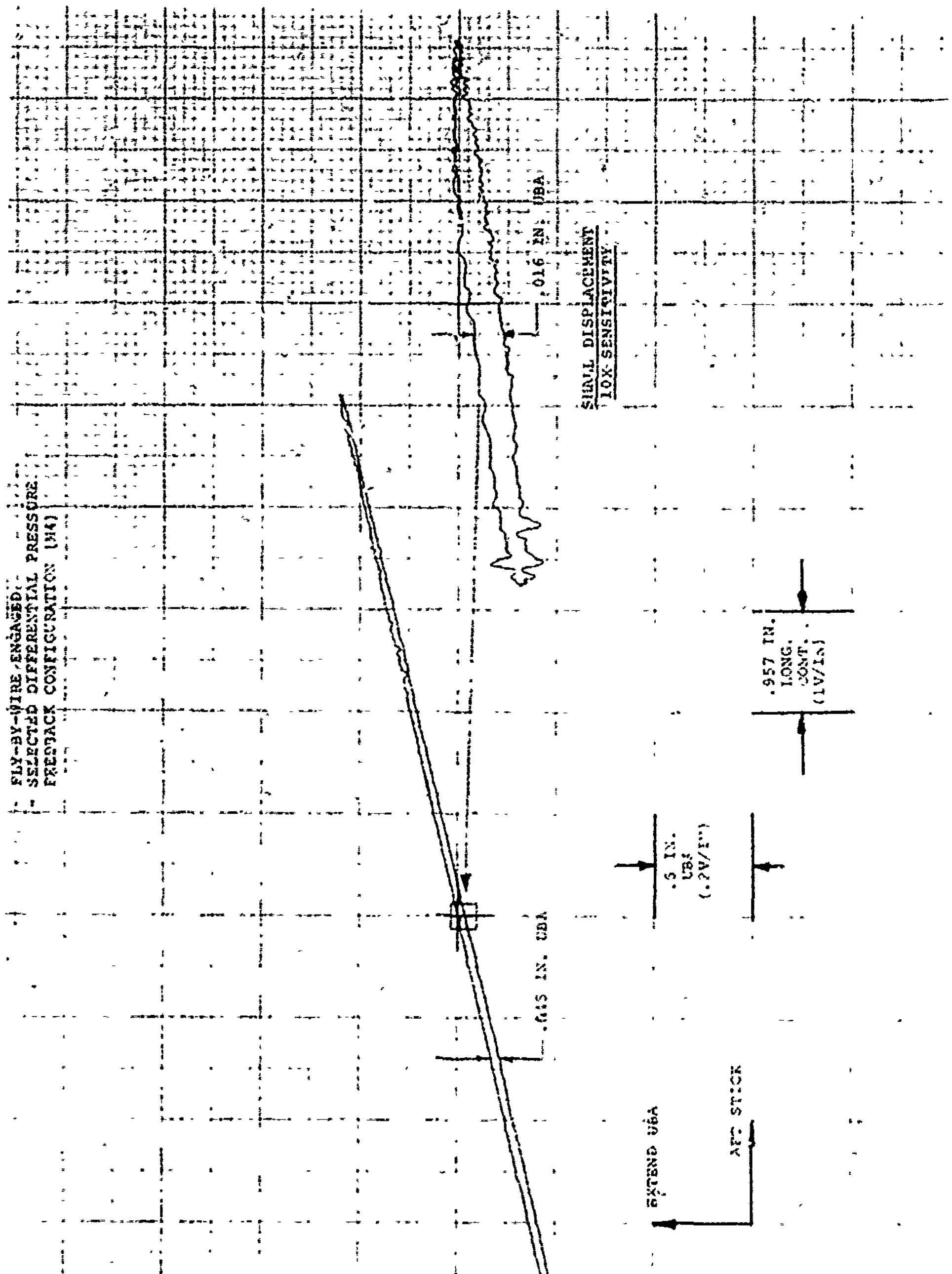


FIGURE E-1. FORWARD RIGHT UPPER BOOST ACTUATOR VS LONGITUDINAL AXIS DISPLACEMENT (TP 16)

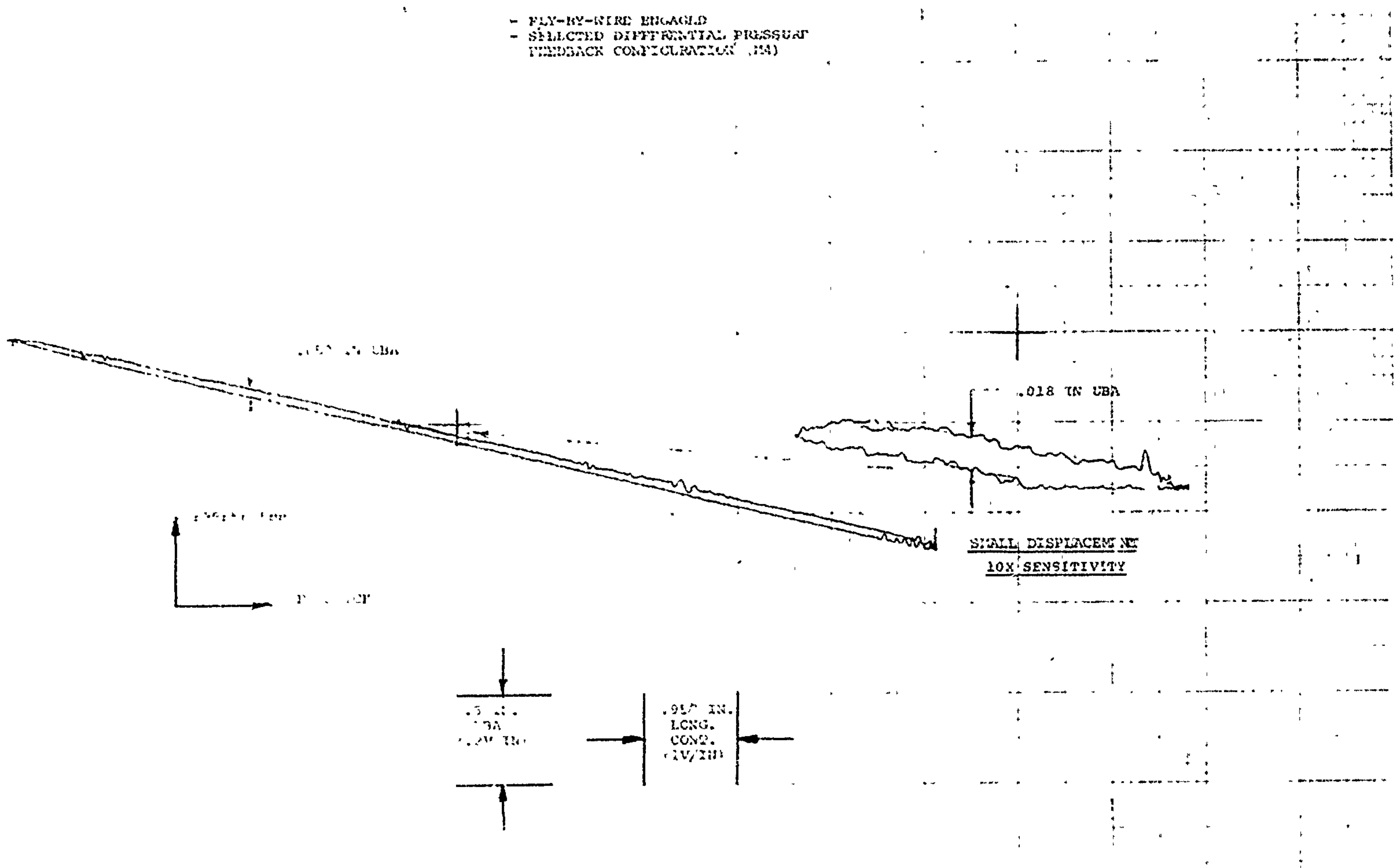


FIGURE E-2. AFT LEFT UPPER BOOST ACTUATOR VS LONGITUDINAL AXIS DISPLACEMENT (TP 16)

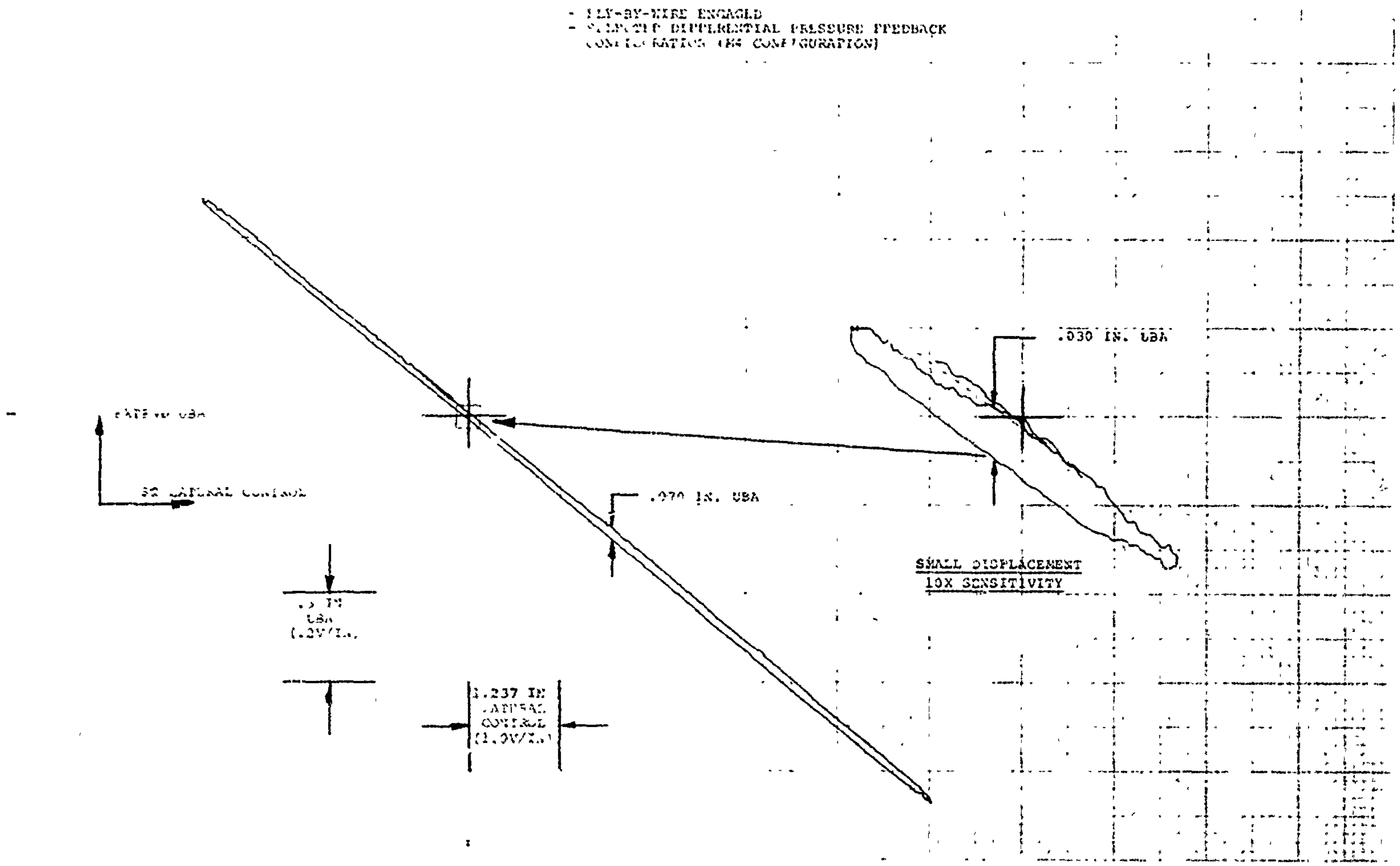


FIGURE E-3. FORWARD RIGHT UPPER BOOST ACTUATOR LATERAL AXIS DISPLACEMENT (TP 17)

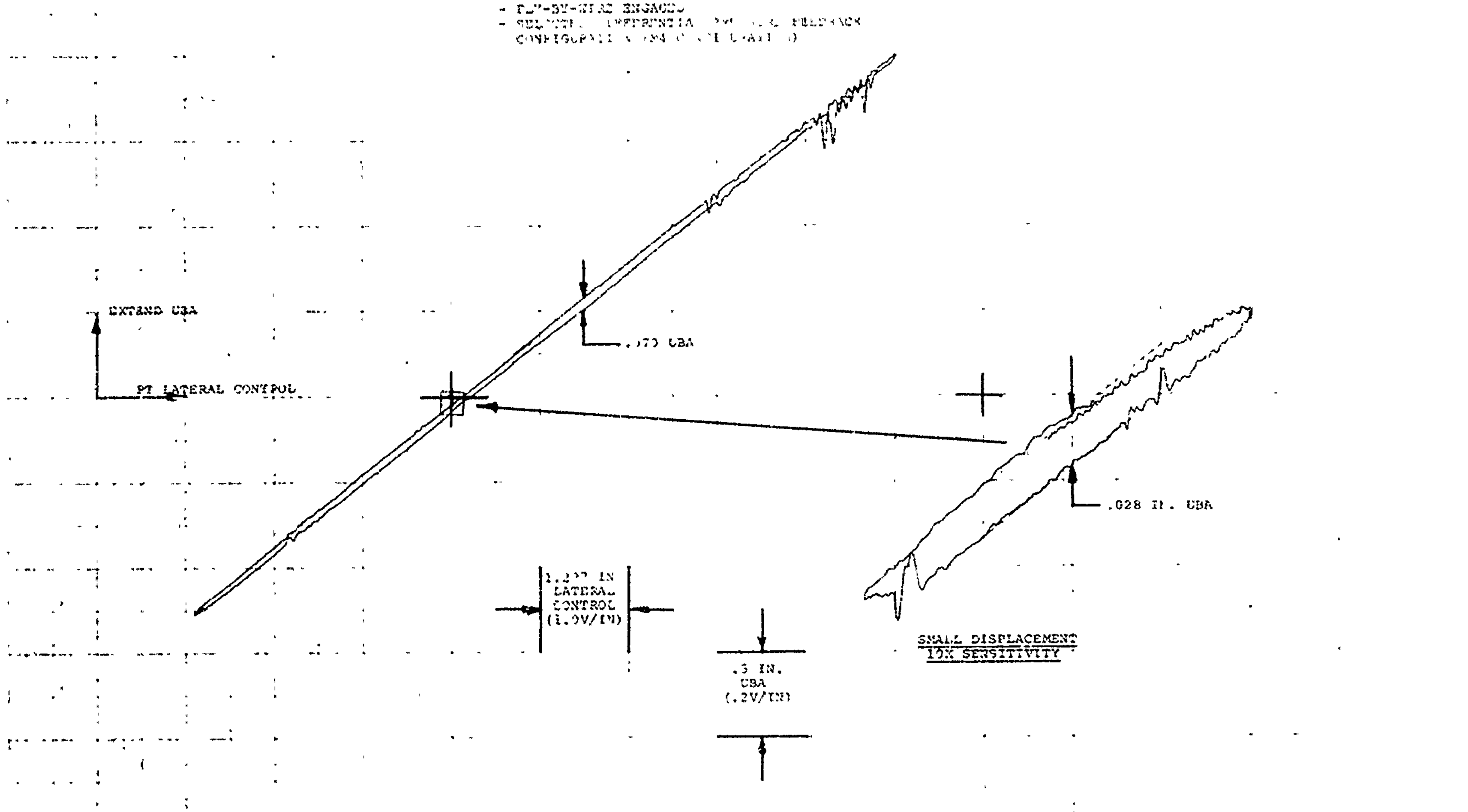


FIGURE E-4. AFT LEFT UPPER BOOST ACTUATOR VS LATERAL AXIS DISPLACEMENT (TP 17)

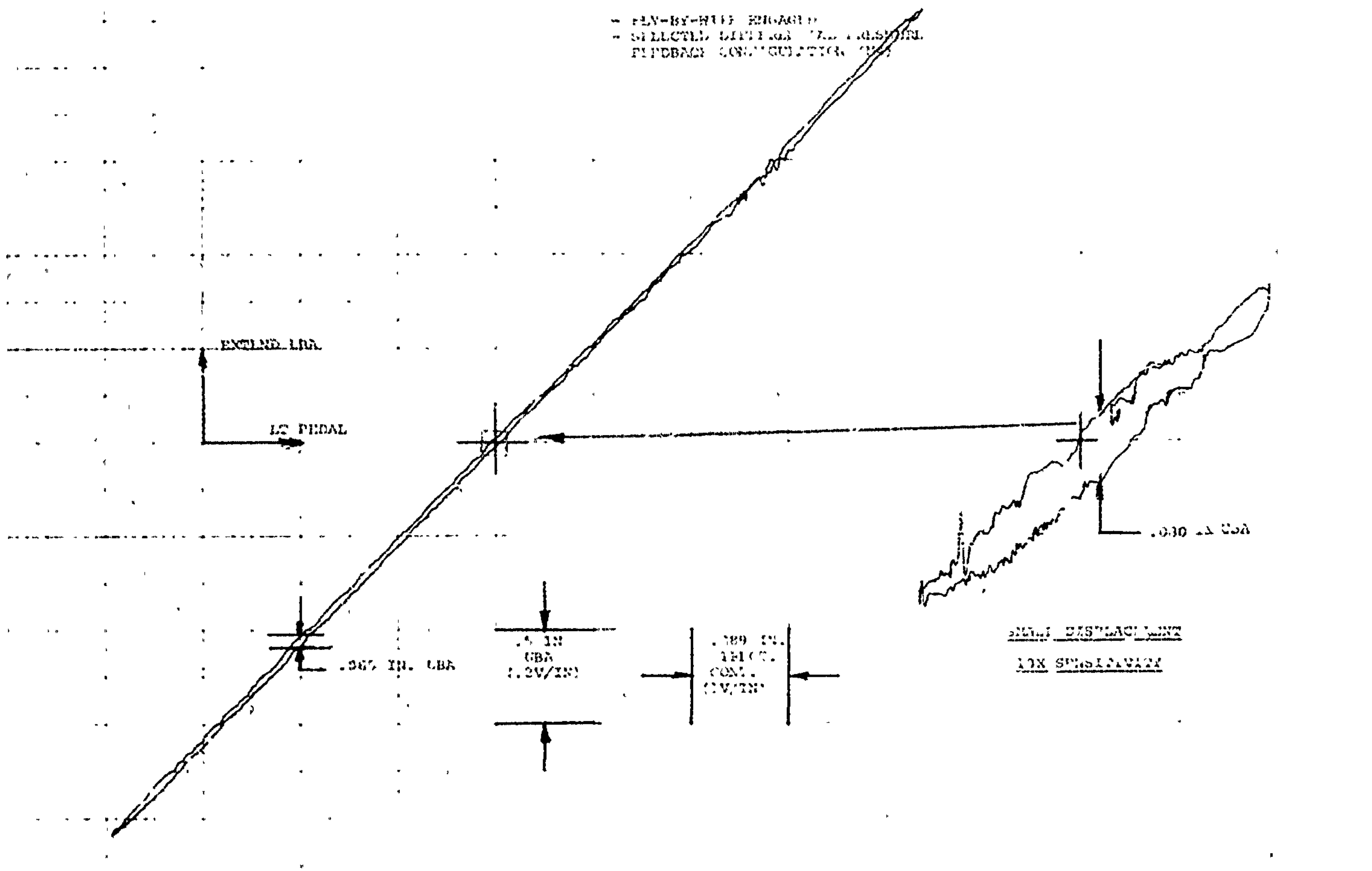


FIGURE E-5. FORWARD RIGHT UPPER BOOST ACTUATOR'S DIRECTIONAL AXIS DISPLACEMENT (TP 18)

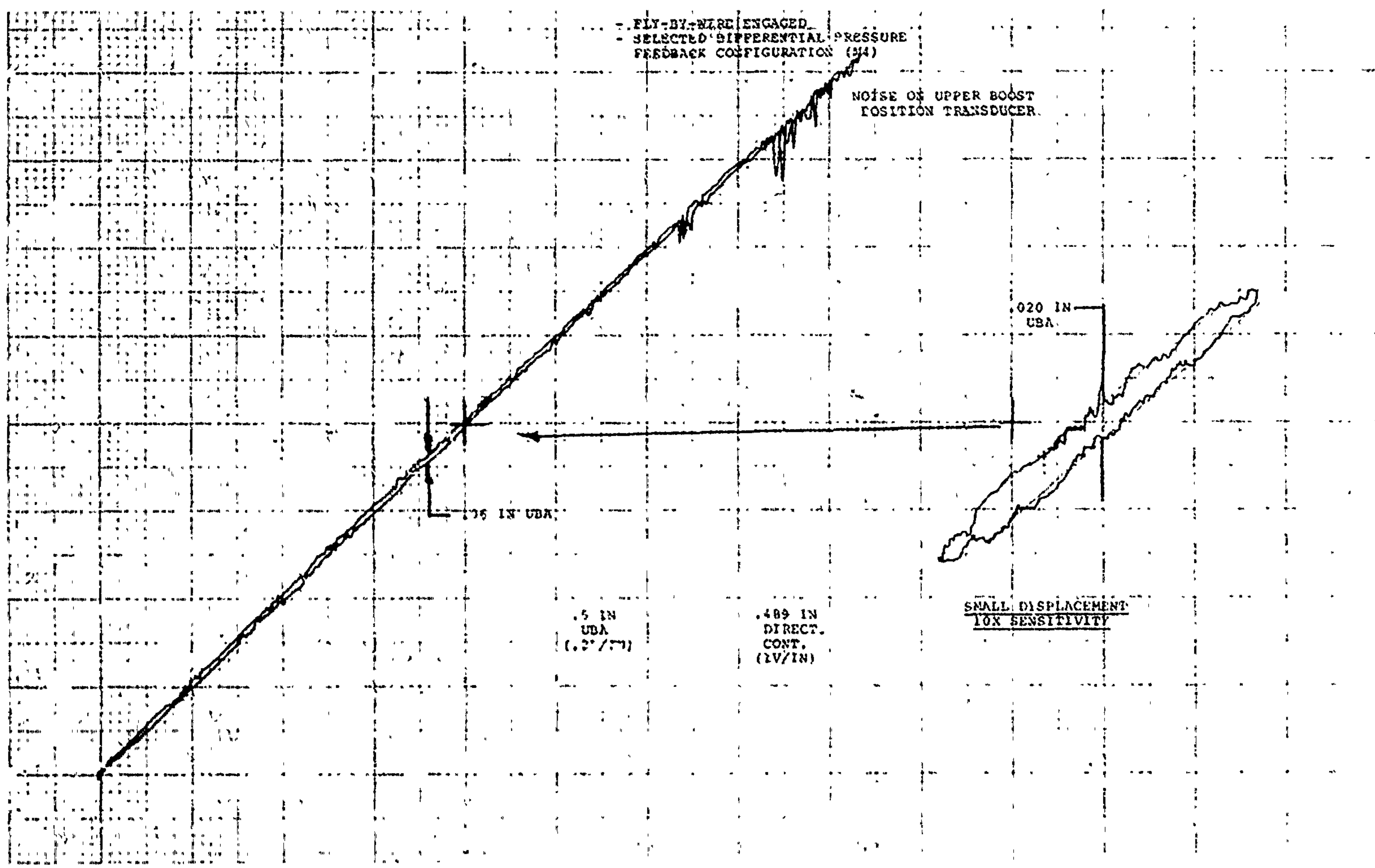


FIGURE E-6. AFT LEFT UPPER BOOST ACTUATOR VS DIRECTIONAL AXIS DISPLACEMENT (TP 18)

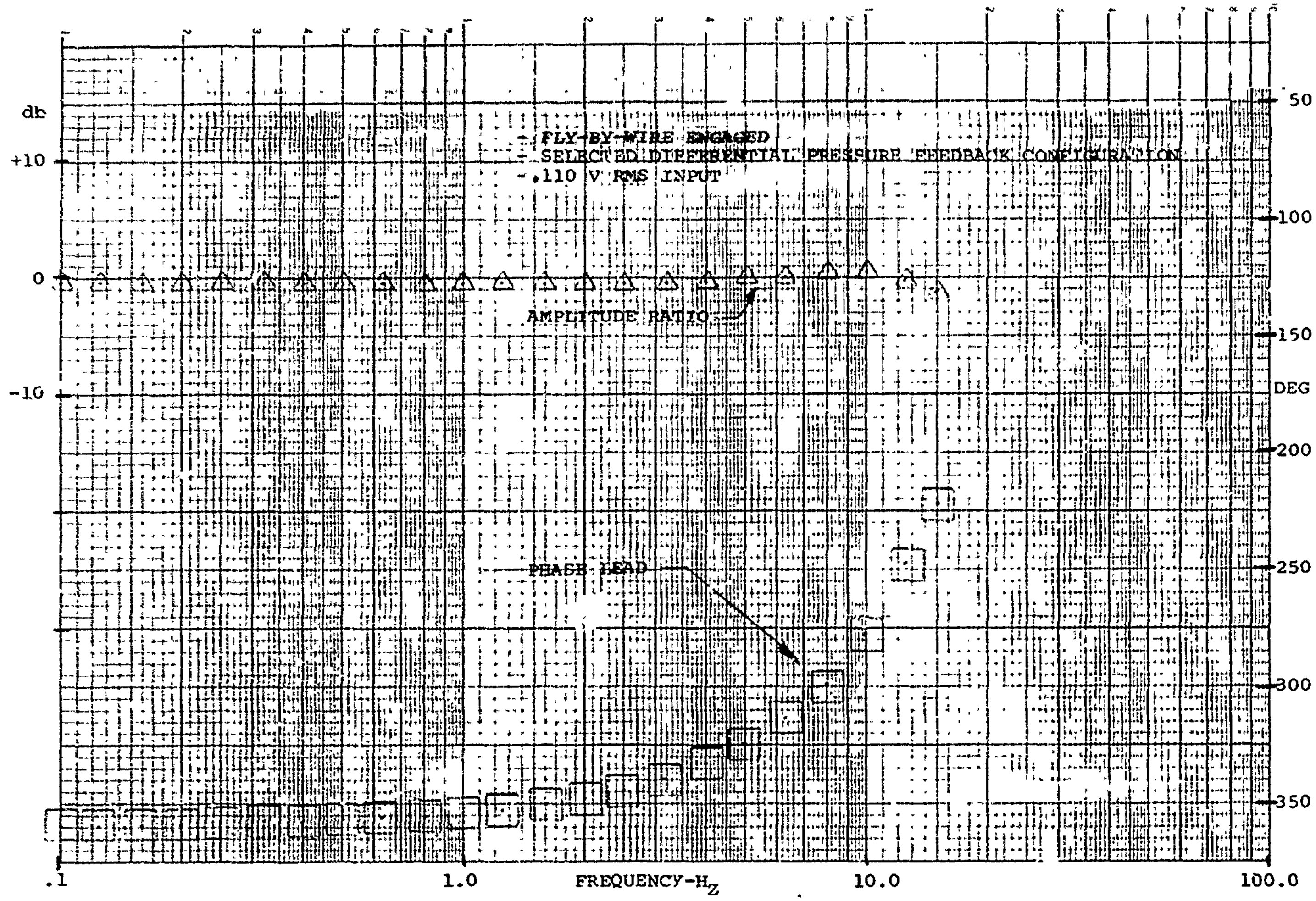


FIGURE E-7. LONGITUDINAL SAS ACTUATOR (TP-25) VS LONGITUDINAL SAS COMMAND

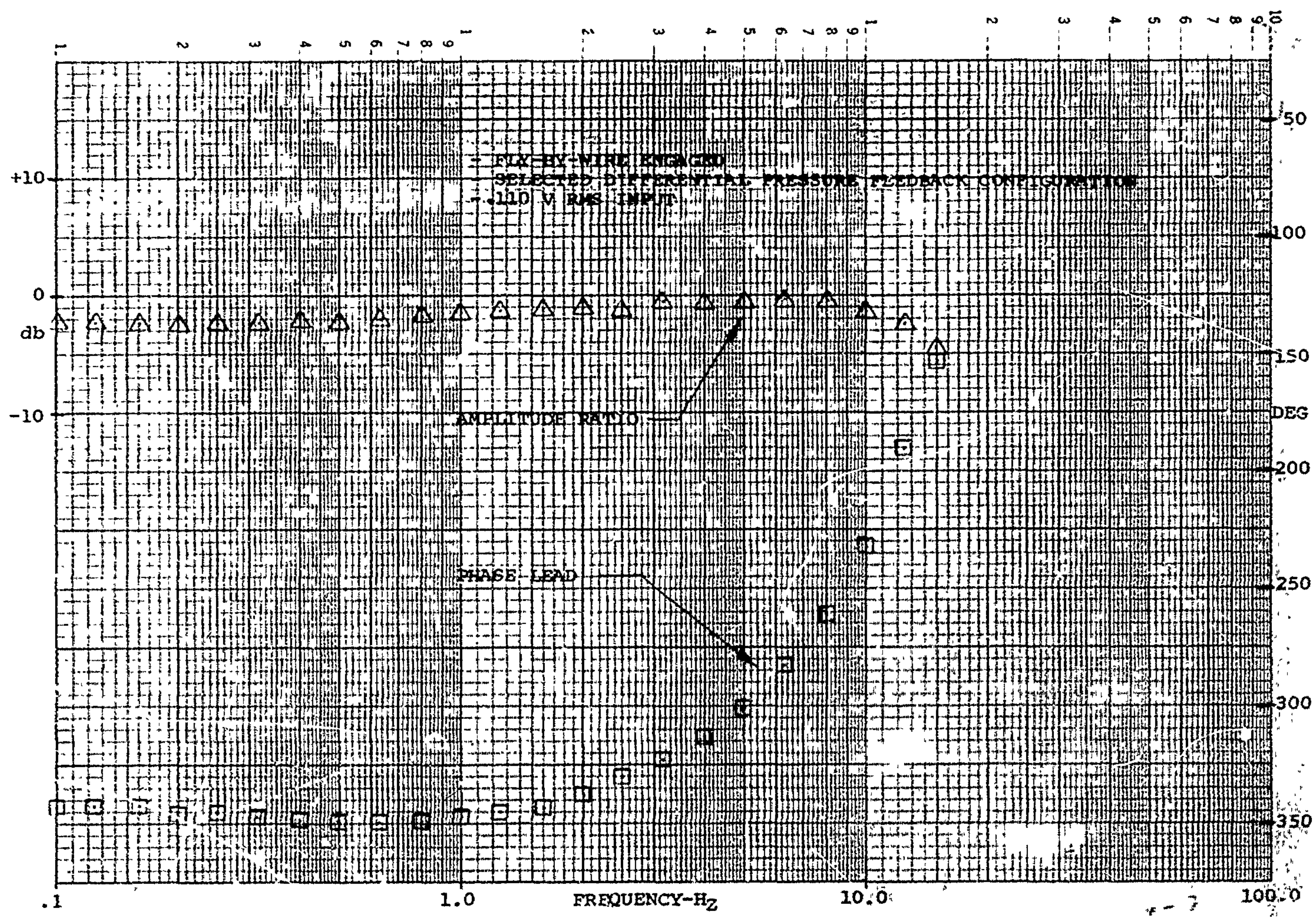


FIGURE E-8. FORWARD RIGHT FLY-BY-WIRE ACTUATOR (TP 34) VS LONGITUDINAL SAS COMMAND

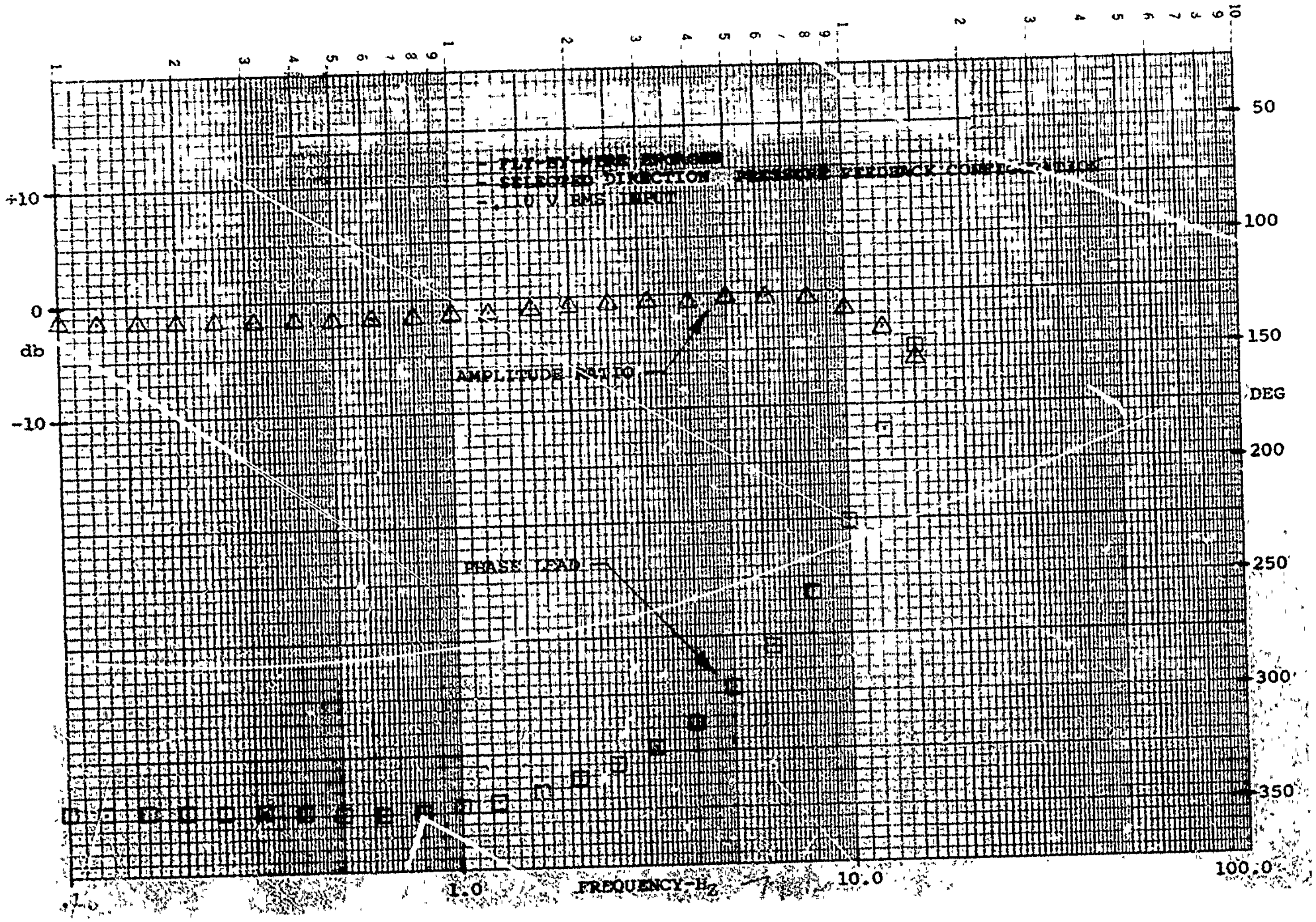


FIGURE E-9. AFT LEFT FLY-BY-WIRE ACTUATOR (TP-46) VS LONGITUDINAL SAS COMMAND

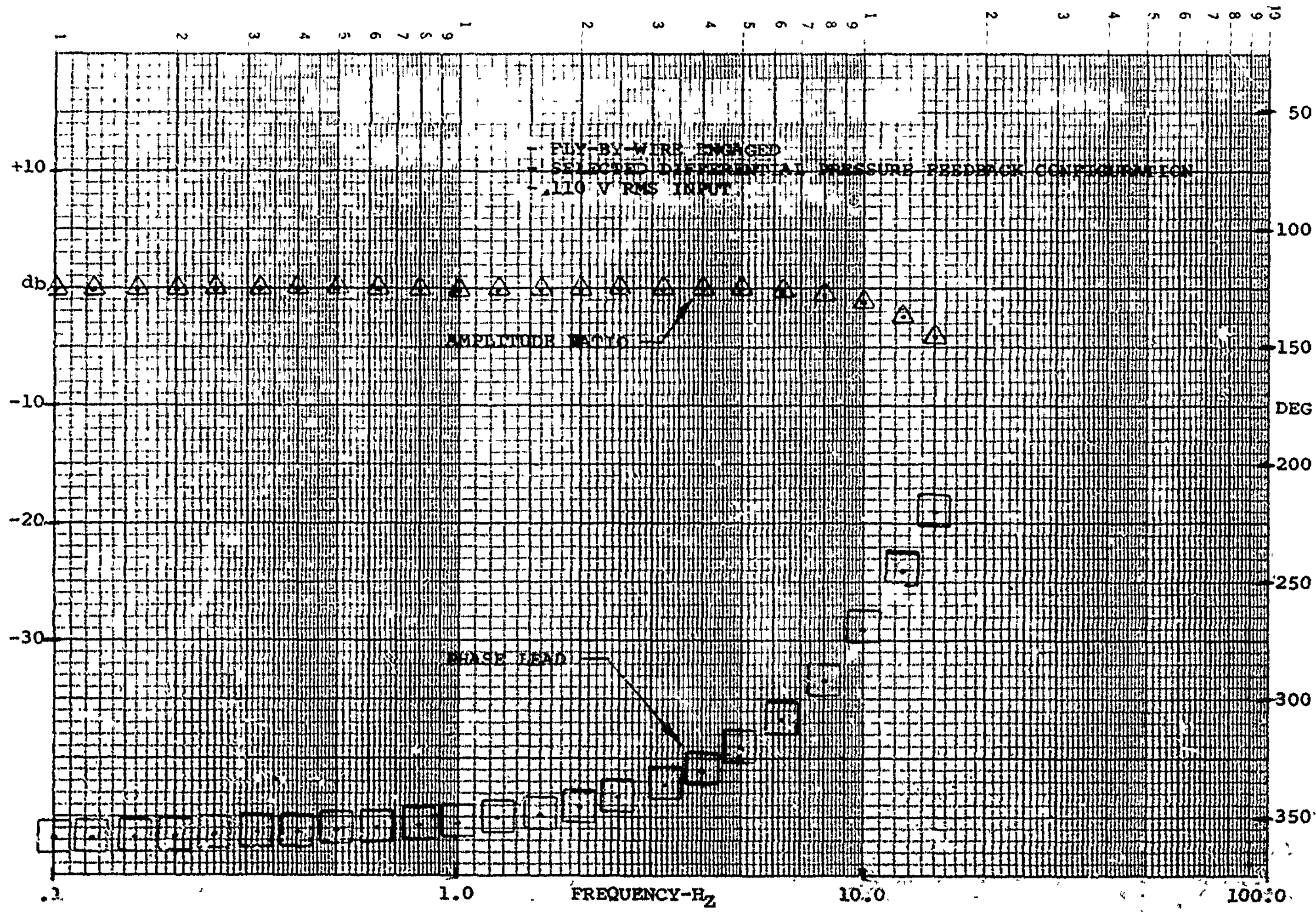


FIGURE E-10. DIRECTIONAL SAS ACTUATOR (TP 31) VS DIRECTIONAL SAS COMMAND

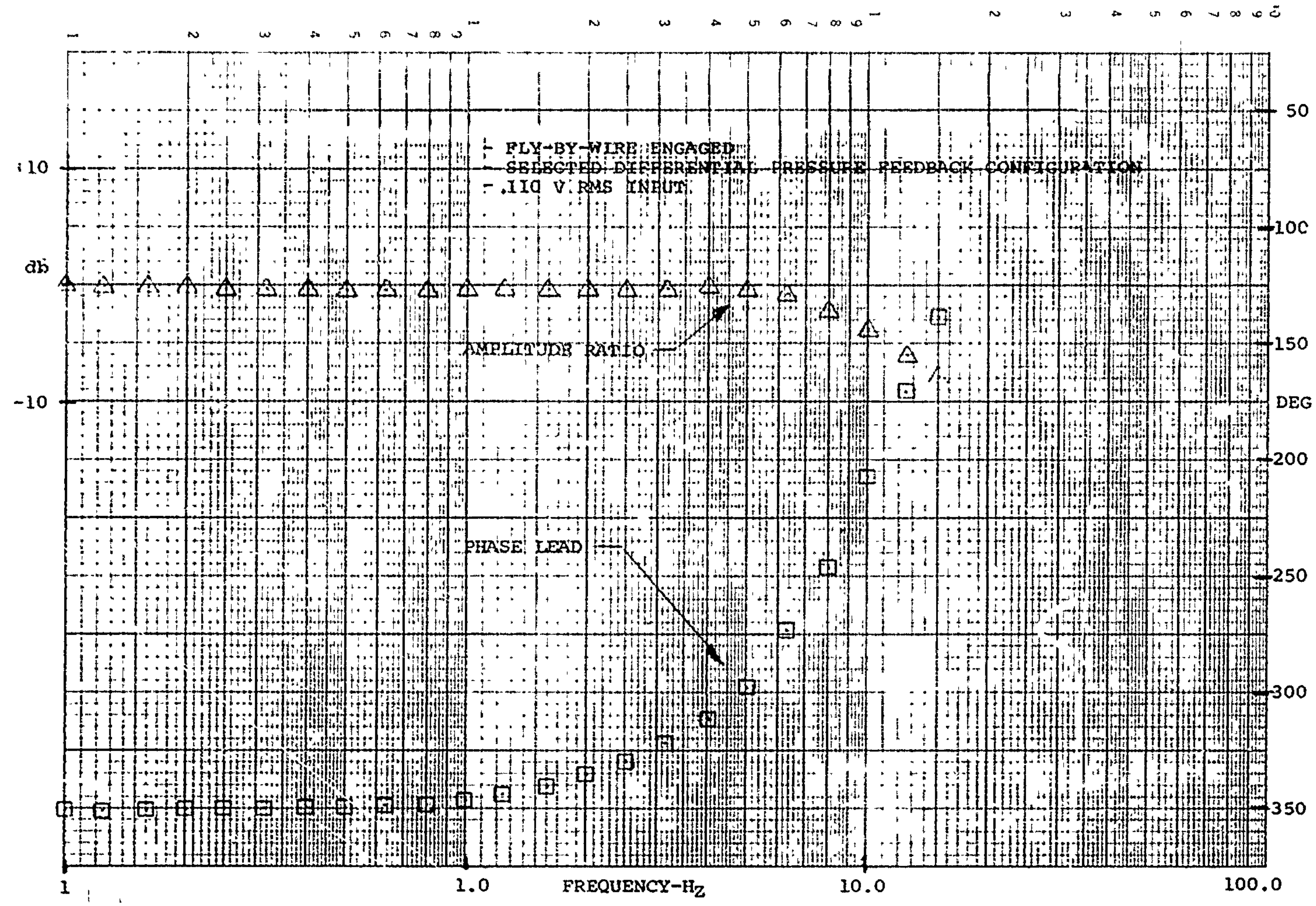


FIGURE E-11. FORWARD RIGHT FLY-BY-WIRE ACTUATOR (TP 34) VS DIRECTIONAL SAS COMMAND

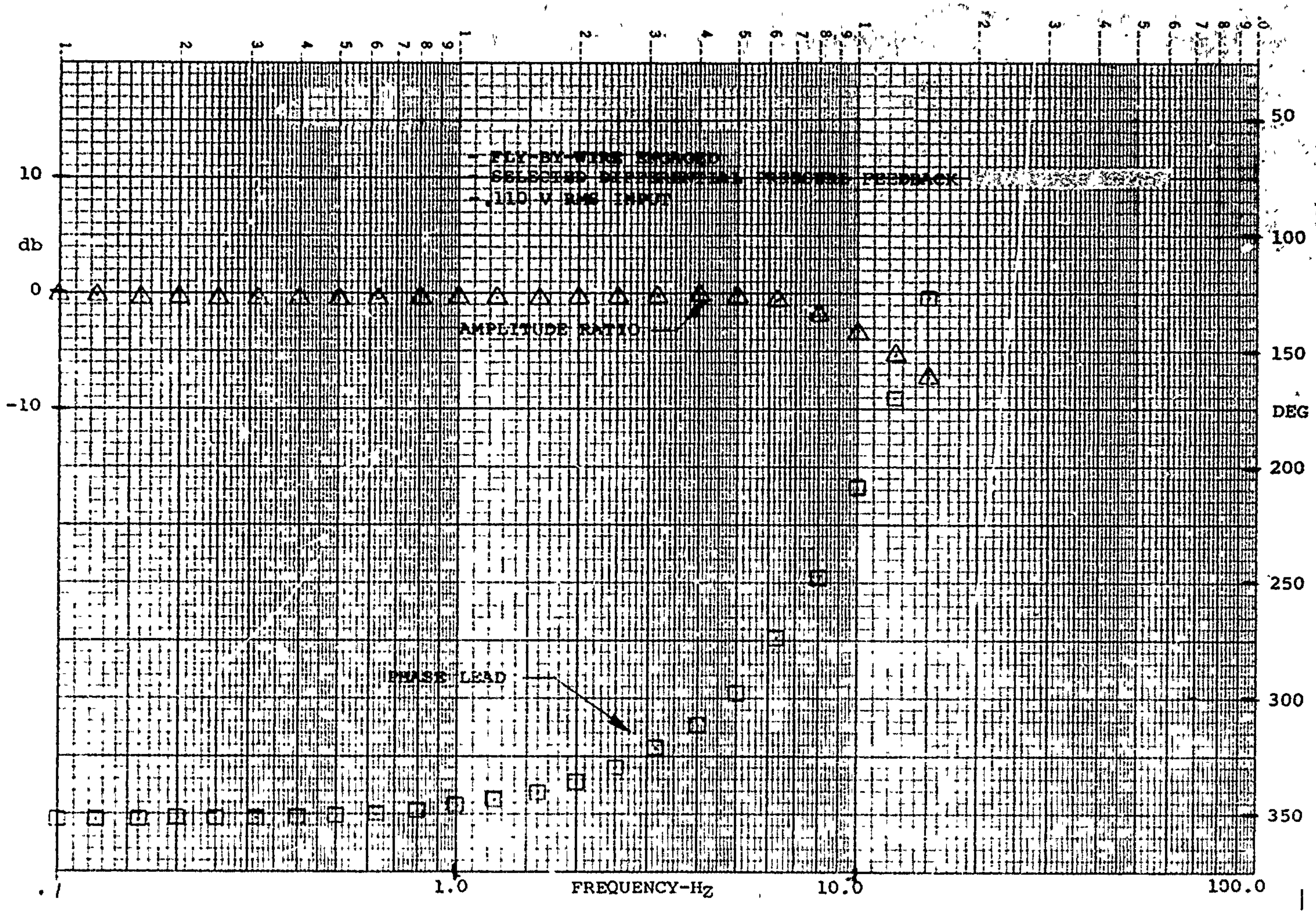
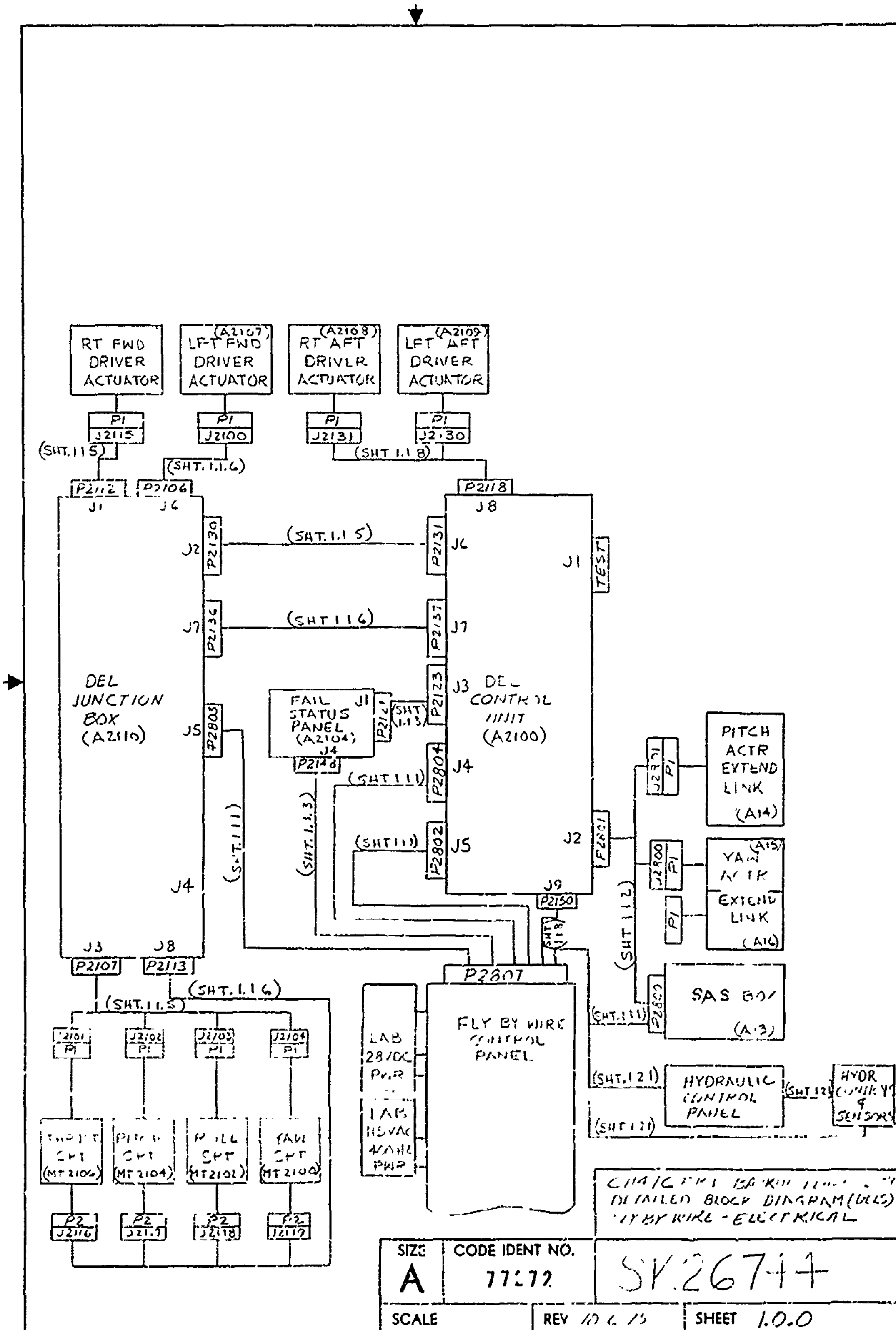
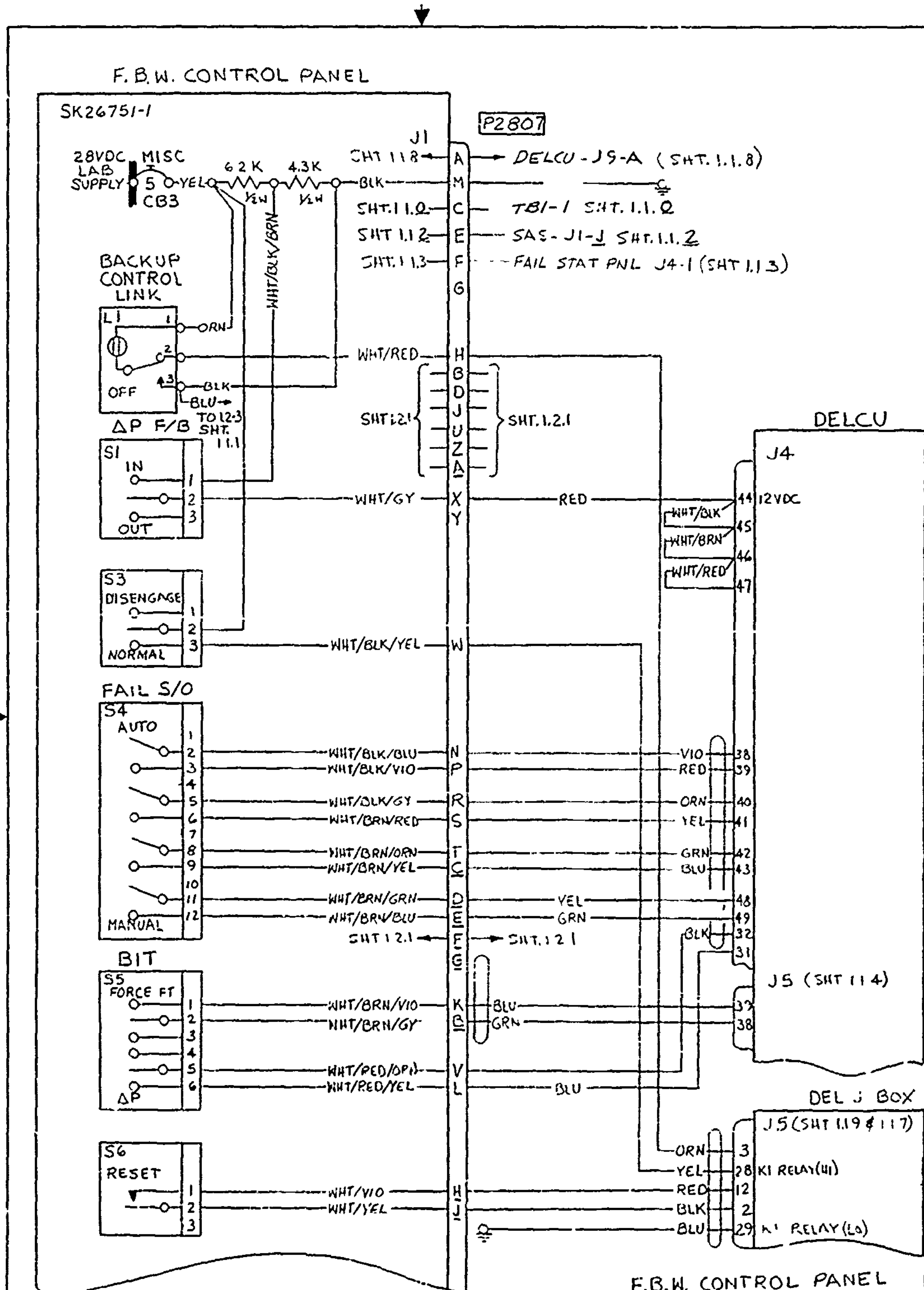


FIGURE E-12. AFT LEFT FLY-BY-WIRE ACTUATOR (TP 46) VS DIRECTIONAL SAS COMMAND

APPENDIX F

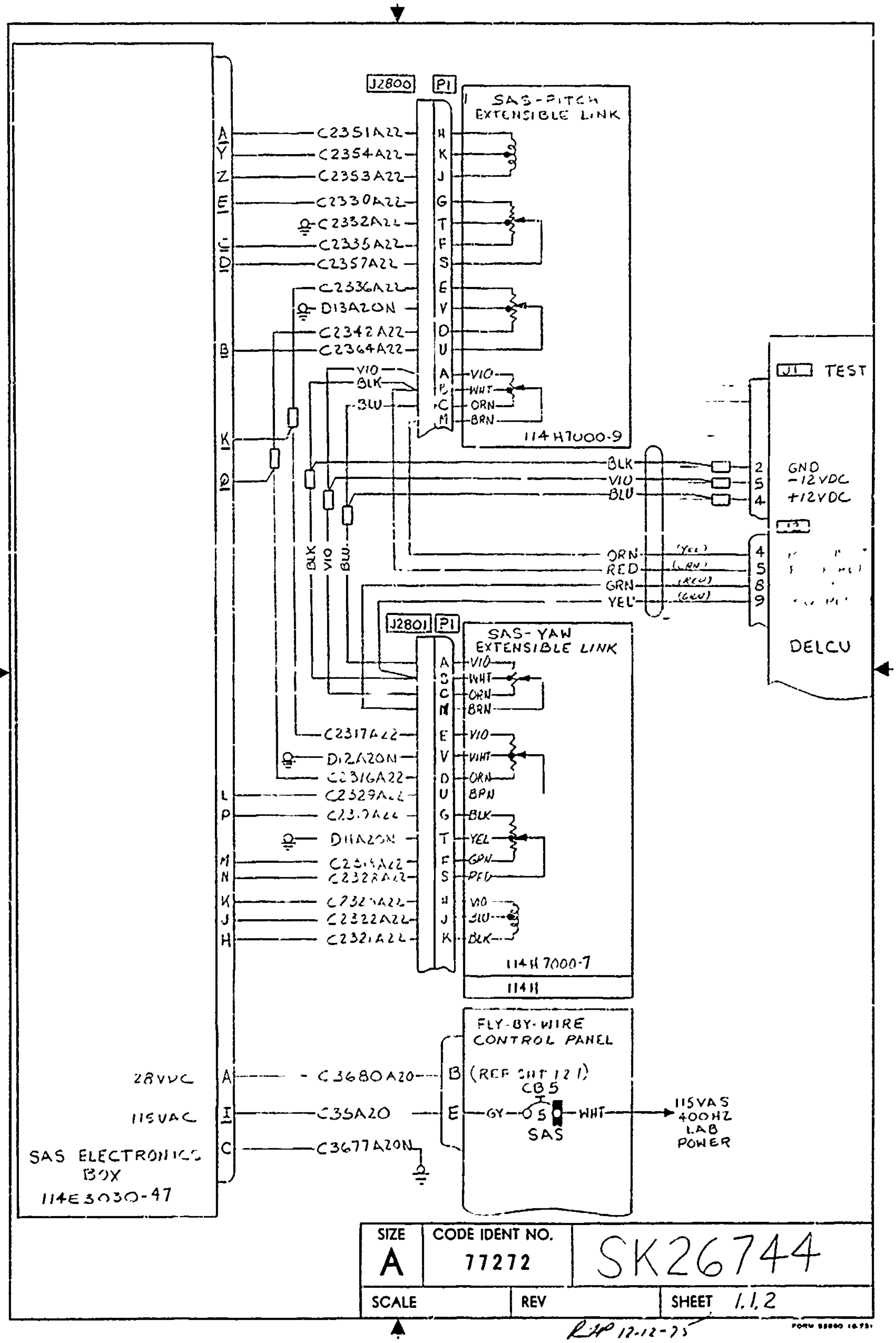
CH-47C ELECTRICAL SYSTEM DIAGRAMS



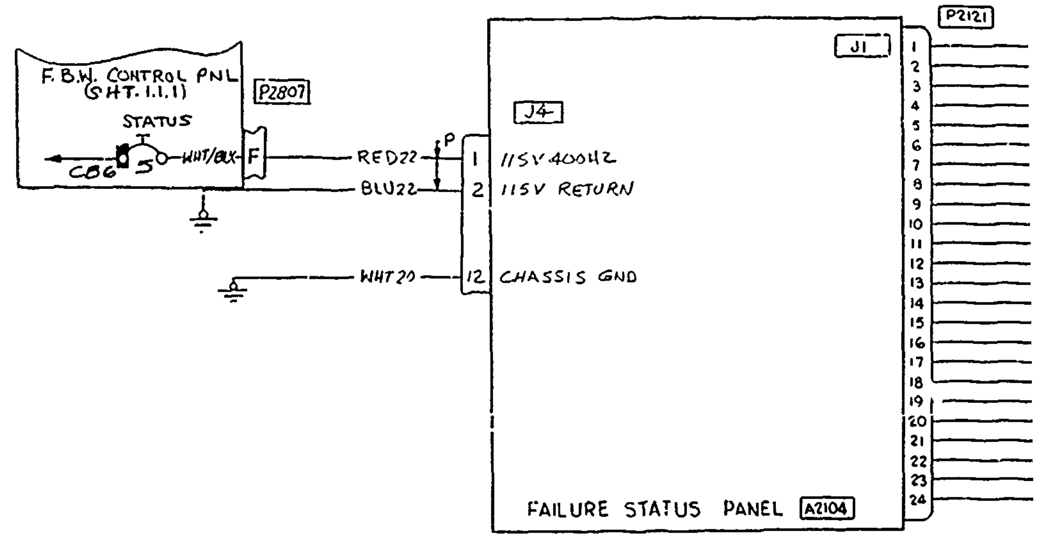


SIZE	CODE IDENT NO.	
A	77272	SK 26744
SCALE	REV 10-6-75	SHEET 1.1.1

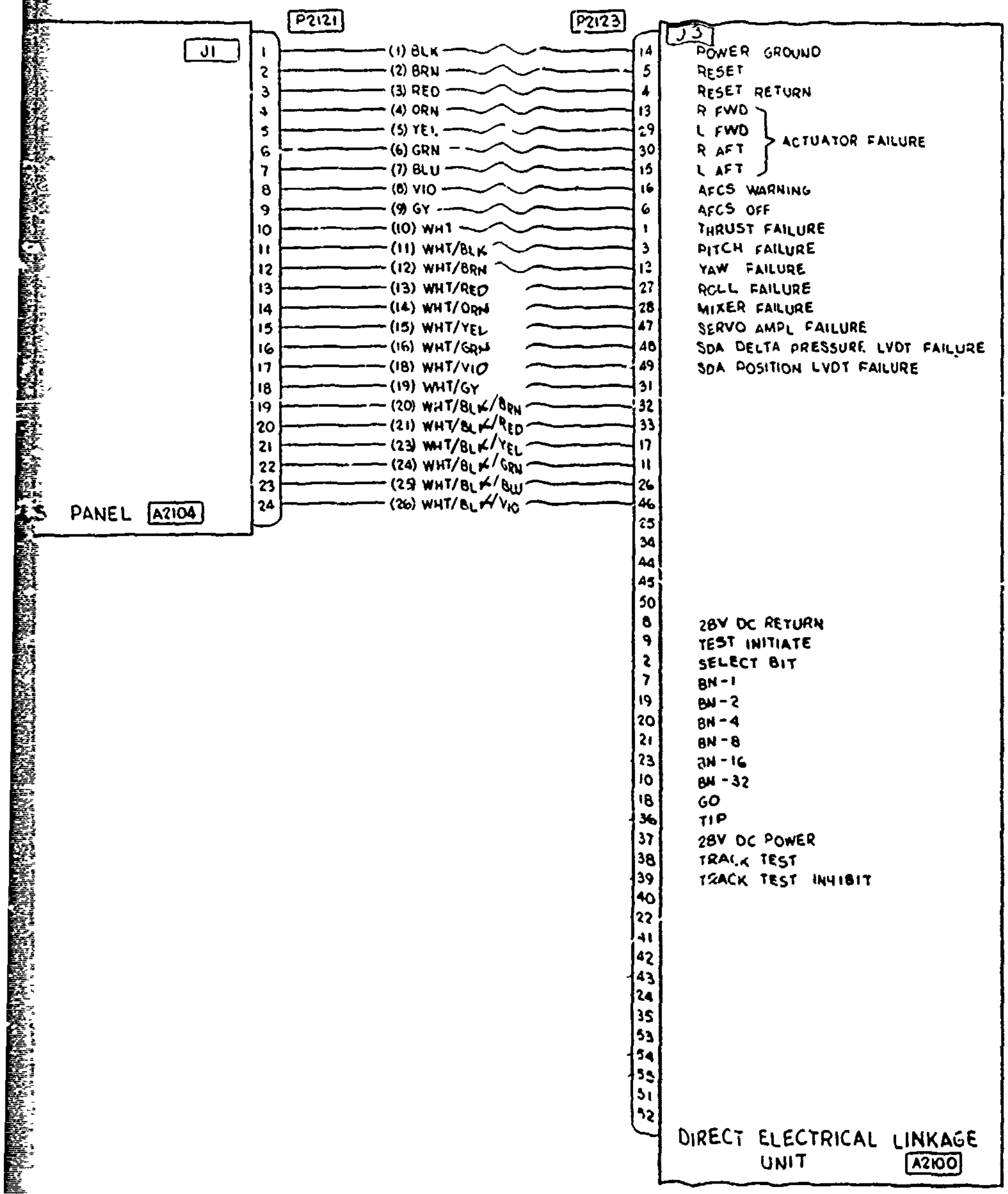
FORM 93660 (6-73)



J2800
P1
SAS-PITCH EXTENSIBLE LINK
114H7000-9
J1 TEST
GND
-12VDC
+12VDC
DELCU
J2801
P1
SAS-YAW EXTENSIBLE LINK
114H7000-7
FLY-BY-WIRE CONTROL PANEL
(REF SHT 121)
CB5
SAS
115VAS 400HZ LAB POWER
28VDC
115VAC
SAS ELECTRONICS BOX
114E3030-47
C2351A22
C2354A22
C2353A22
C2330A22
C2332A22
C2335A22
C2357A22
C2336A22
D13A20N
C2342A22
C2364A22
C2317A22
D12A20N
C2316A22
C3680A20
C35A20
C3677A20N
BLK
VIO
BLU
ORN
RED
GRN
YEL
WHT
BRN
SIZE
A
CODE IDENT NO.
77272
SK26744
SCALE
REV
SHEET 1,1,2



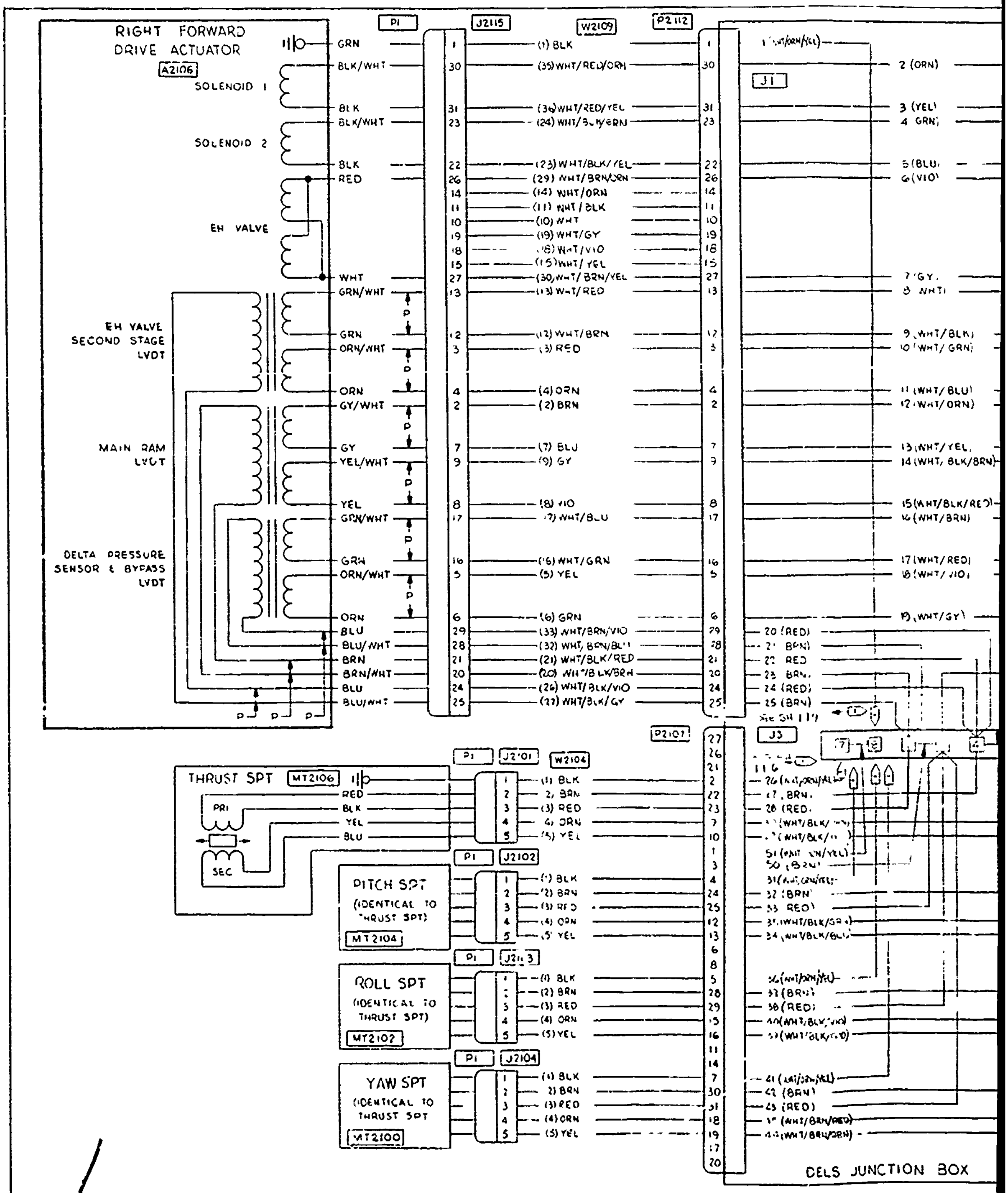
F.B.W. CONTROL PNL
(SHT. 1.1.1)
P2807
STATUS
CB6
S
WHT/BLK
F
RED22
BLU22
WHT20
P
J4
1 115V 400HZ
2 115V RETURN
12 CHASSIS GND
J1
P2121
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
FAILURE STATUS PANEL
A2104

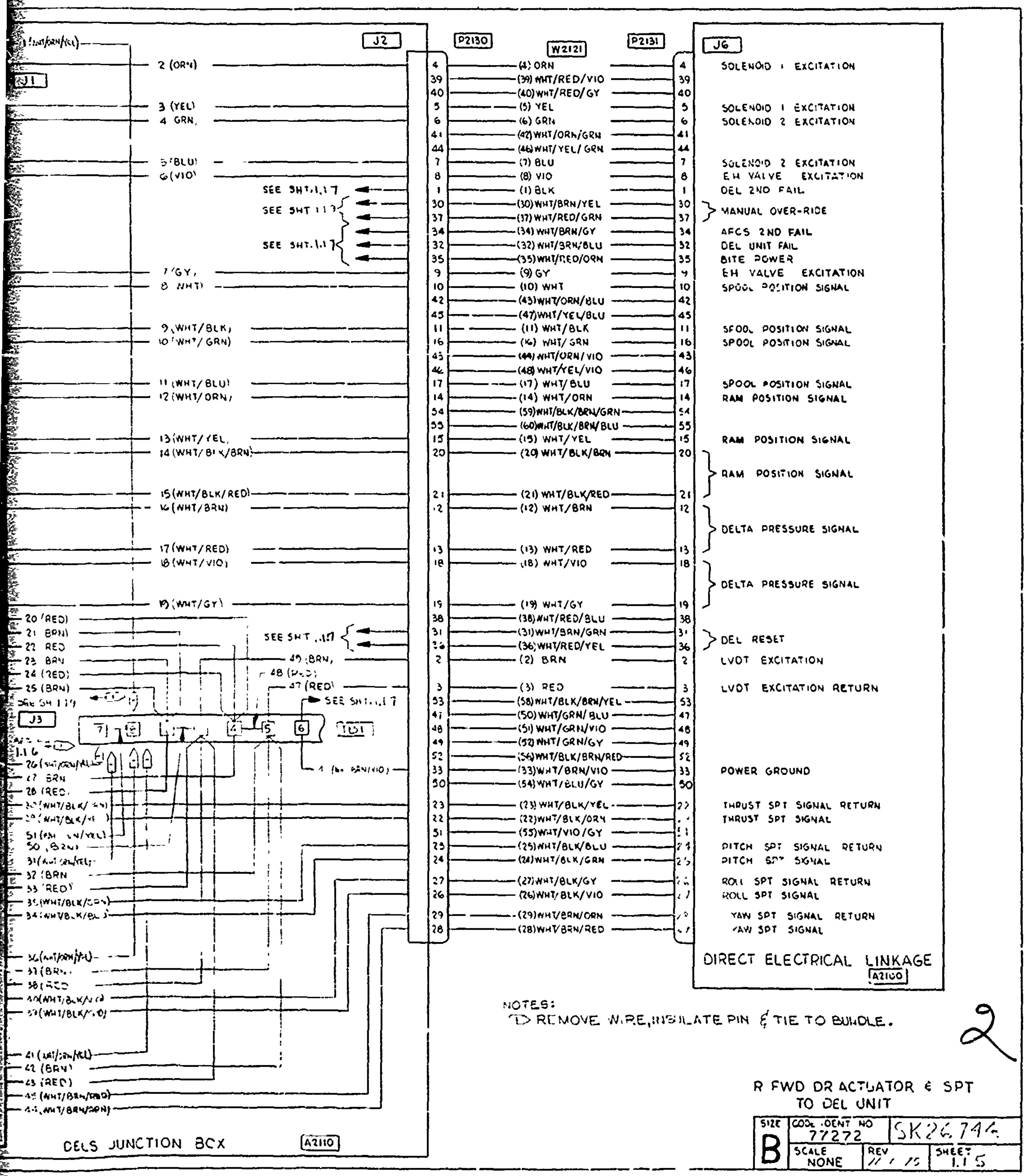


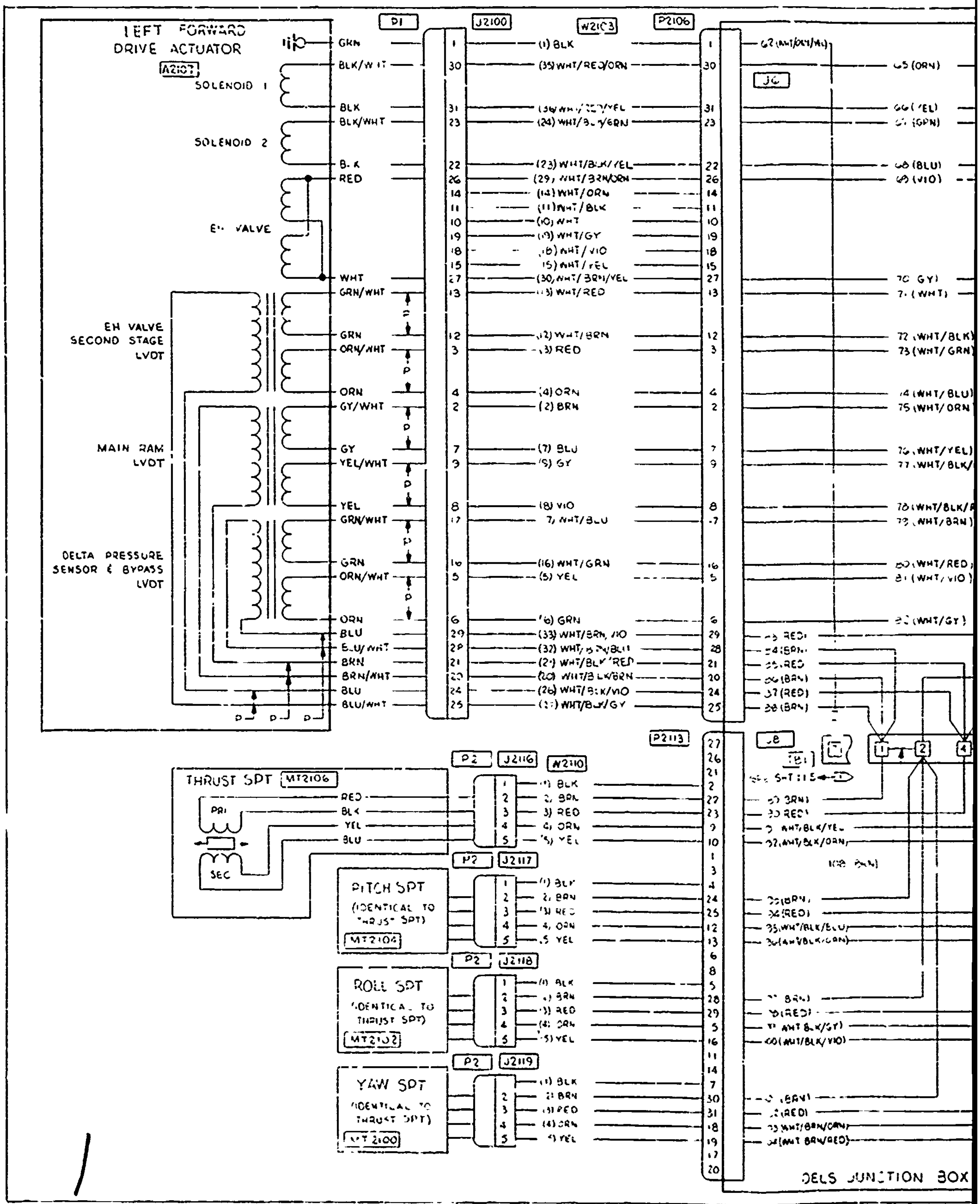
2

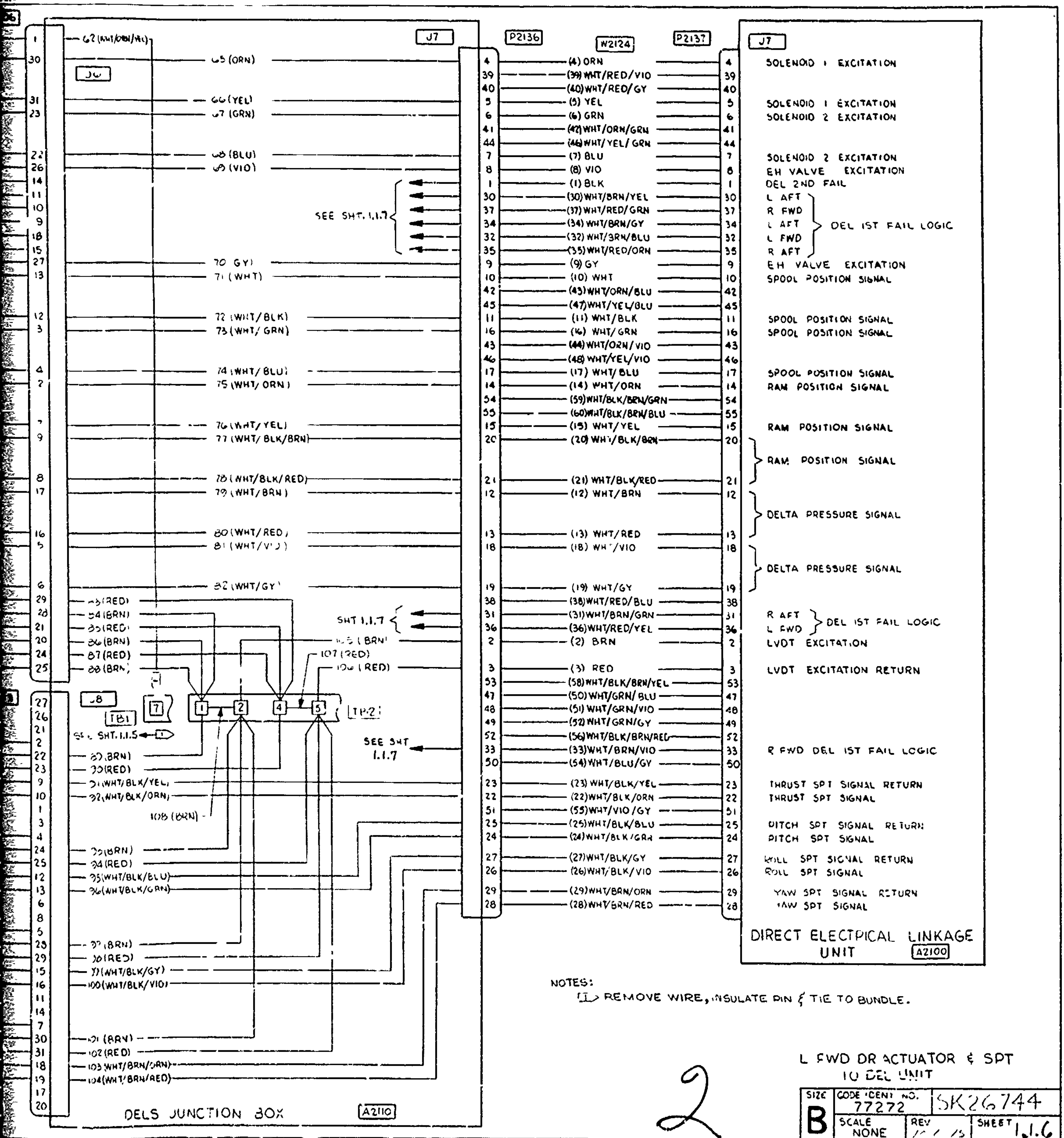
FAILURE STATUS PNL
TO DEL UNIT

SIZE	CODE IDENT NO		
B	77272	SK26744	
	SCALE NONE	REV 10-6-75	SHEET 1.1.3.

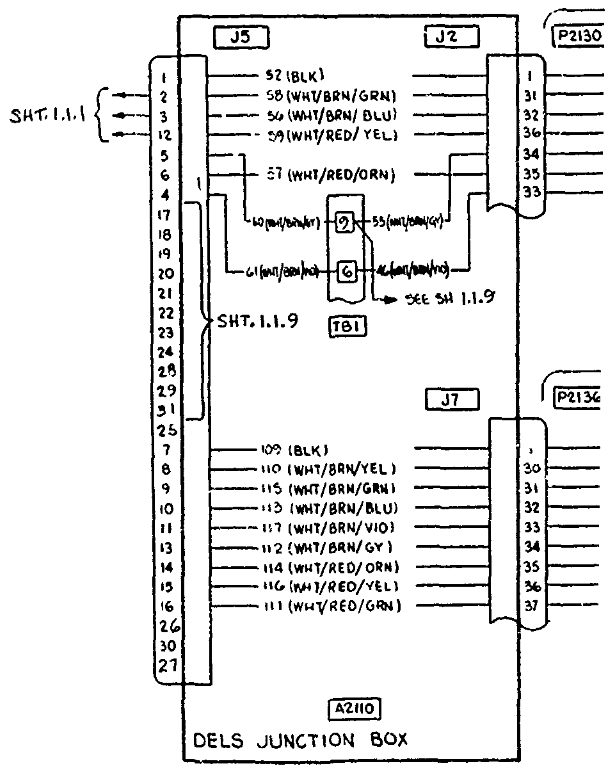

RIGHT FORWARD DRIVE ACTUATOR
A2106
SOLENOID 1
SOLENOID 2
EH VALVE
EH VALVE SECOND STAGE LVDT
MAIN RAM LVDT
DELTA PRESSURE SENSOR & BYPASS LVDT
P1
J2115
W2109
P2112
J1
P2107
J3
THRUST SPT
MT2106
PRI
SEC
PITCH SPT
(IDENTICAL TO THRUST SPT)
MT2104
J2102
ROLL SPT
(IDENTICAL TO THRUST SPT)
MT2102
YAW SPT
(IDENTICAL TO THRUST SPT)
MT2100
J2104
W2104
DELS JUNCTION BOX

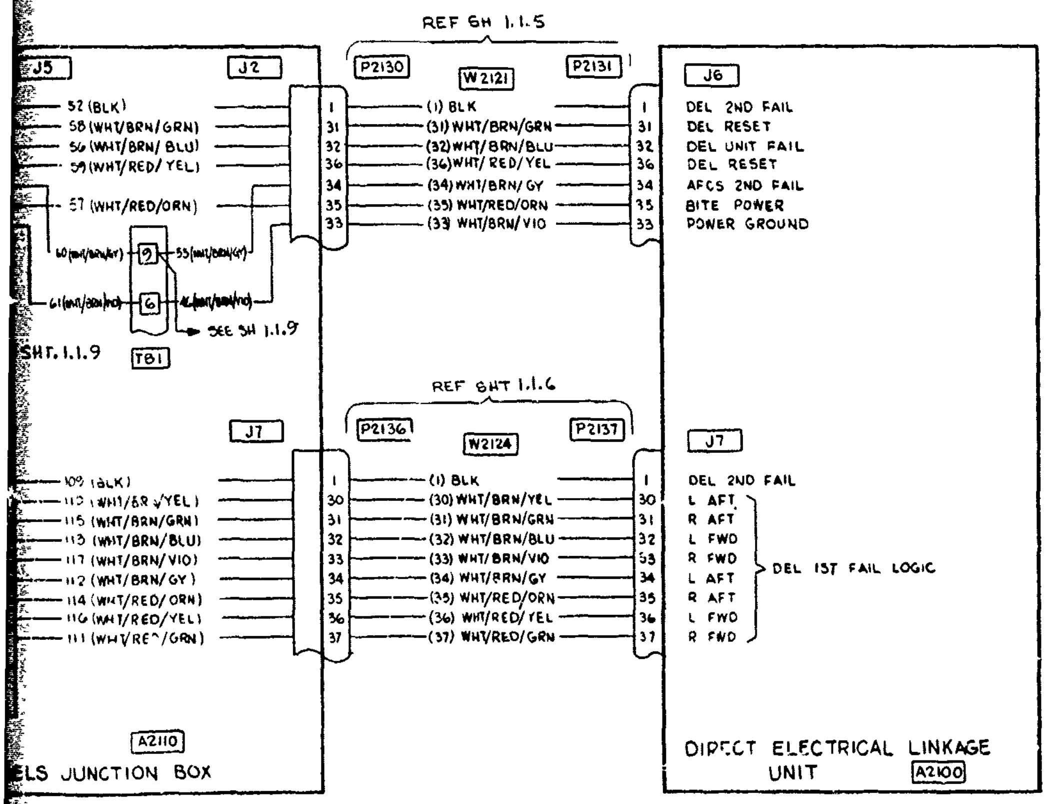

J2
P2130
W2121
P2131
J6
J1
J3
SOLENOID 1 EXCITATION
SOLENOID 1 EXCITATION
SOLENOID 2 EXCITATION
SOLENOID 2 EXCITATION
EH VALVE EXCITATION
DEL 2ND FAIL
MANUAL OVER-RIDE
AFCS 2ND FAIL
DEL UNIT FAIL
BITE POWER
EH VALVE EXCITATION
SPOOL POSITION SIGNAL
SPOOL POSITION SIGNAL
SPOOL POSITION SIGNAL
SPOOL POSITION SIGNAL
RAM POSITION SIGNAL
RAM POSITION SIGNAL
RAM POSITION SIGNAL
DELTA PRESSURE SIGNAL
DELTA PRESSURE SIGNAL
DEL RESET
LVDT EXCITATION
LVDT EXCITATION RETURN
POWER GROUND
THRUST SPT SIGNAL RETURN
THRUST SPT SIGNAL
PITCH SPT SIGNAL RETURN
PITCH SPT SIGNAL
ROLL SPT SIGNAL RETURN
ROLL SPT SIGNAL
YAW SPT SIGNAL RETURN
YAW SPT SIGNAL
DIRECT ELECTRICAL LINKAGE
A2100
DELS JUNCTION BOX
A2110
NOTES:
1 REMOVE WIRE, INSULATE PIN & TIE TO BUNDLE.
2
R FWD DR ACTUATOR & SPT
TO DEL UNIT
SIZE
B
CODE IDENT NO
77272
SK26744
SCALE
NONE
REV
SHEET
1.15


LEFT FORWARD DRIVE ACTUATOR
A2107
SOLENOID 1
SOLENOID 2
EH VALVE
EH VALVE SECOND STAGE LVDT
MAIN RAM LVDT
DELTA PRESSURE SENSOR & BYPASS LVDT
P1
J2100
W2103
P2106
J6
P2113
J8
THRUST SPT
MT2106
PRI
SEC
P2
J2116
W2110
J2117
PITCH SPT
(IDENTICAL TO THRUST SPT)
MT2104
J2118
ROLL SPT
(IDENTICAL TO THRUST SPT)
MT2102
J2119
YAW SPT
(IDENTICAL TO THRUST SPT)
MT2100
DELS JUNCTION BOX



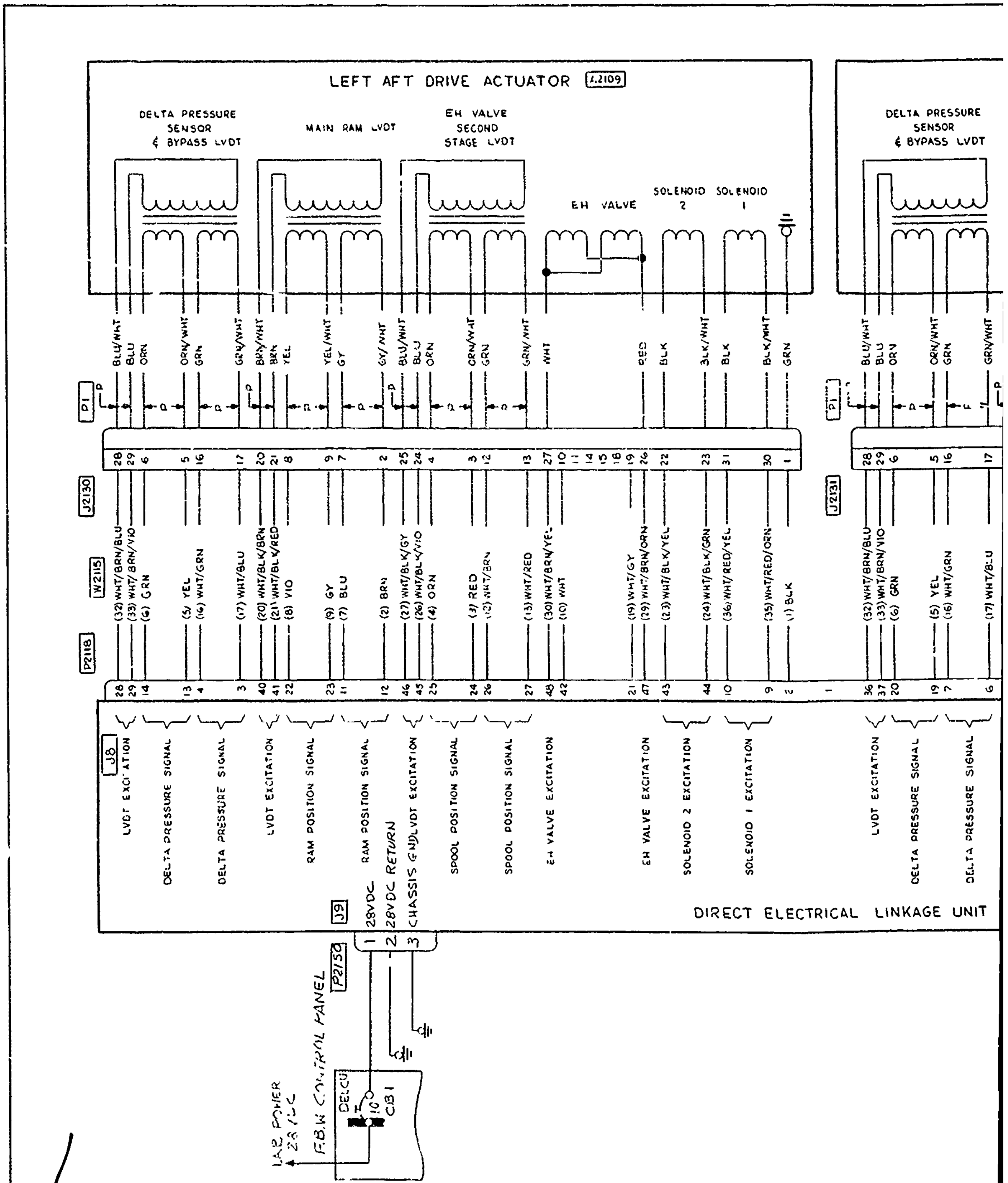
J7
P2136
W2124
P2137
J7
SOLENOID 1 EXCITATION
SOLENOID 1 EXCITATION
SOLENOID 2 EXCITATION
SOLENOID 2 EXCITATION
EH VALVE EXCITATION
DEL 2ND FAIL
L AFT
R FWD
L AFT
L FWD
R AFT
DEL 1ST FAIL LOGIC
EH VALVE EXCITATION
SPOOL POSITION SIGNAL
SPOOL POSITION SIGNAL
SPOOL POSITION SIGNAL
SPOOL POSITION SIGNAL
RAM POSITION SIGNAL
RAM POSITION SIGNAL
RAM POSITION SIGNAL
DELTA PRESSURE SIGNAL
DELTA PRESSURE SIGNAL
R AFT
L FWD
DEL 1ST FAIL LOGIC
LVDT EXCITATION
LVDT EXCITATION RETURN
R FWD DEL 1ST FAIL LOGIC
THRUST SPT SIGNAL RETURN
THRUST SPT SIGNAL
PITCH SPT SIGNAL RETURN
PITCH SPT SIGNAL
ROLL SPT SIGNAL RETURN
ROLL SPT SIGNAL
YAW SPT SIGNAL RETURN
YAW SPT SIGNAL
DIRECT ELECTRICAL LINKAGE UNIT
A2100
SEE SHT. 1.1.7
SHT 1.1.7
SEE SHT 1.1.7
SEE SHT. 1.1.5
TB1
TB2
DELS JUNCTION BOX
A2110
NOTES:
1 REMOVE WIRE, INSULATE PIN & TIE TO BUNDLE.
L FWD DR ACTUATOR & SPT TO DEL UNIT
SIZE B
CODE IDENT NO. 77272
SK26744
SCALE NONE
SHEET 1.1.6
2

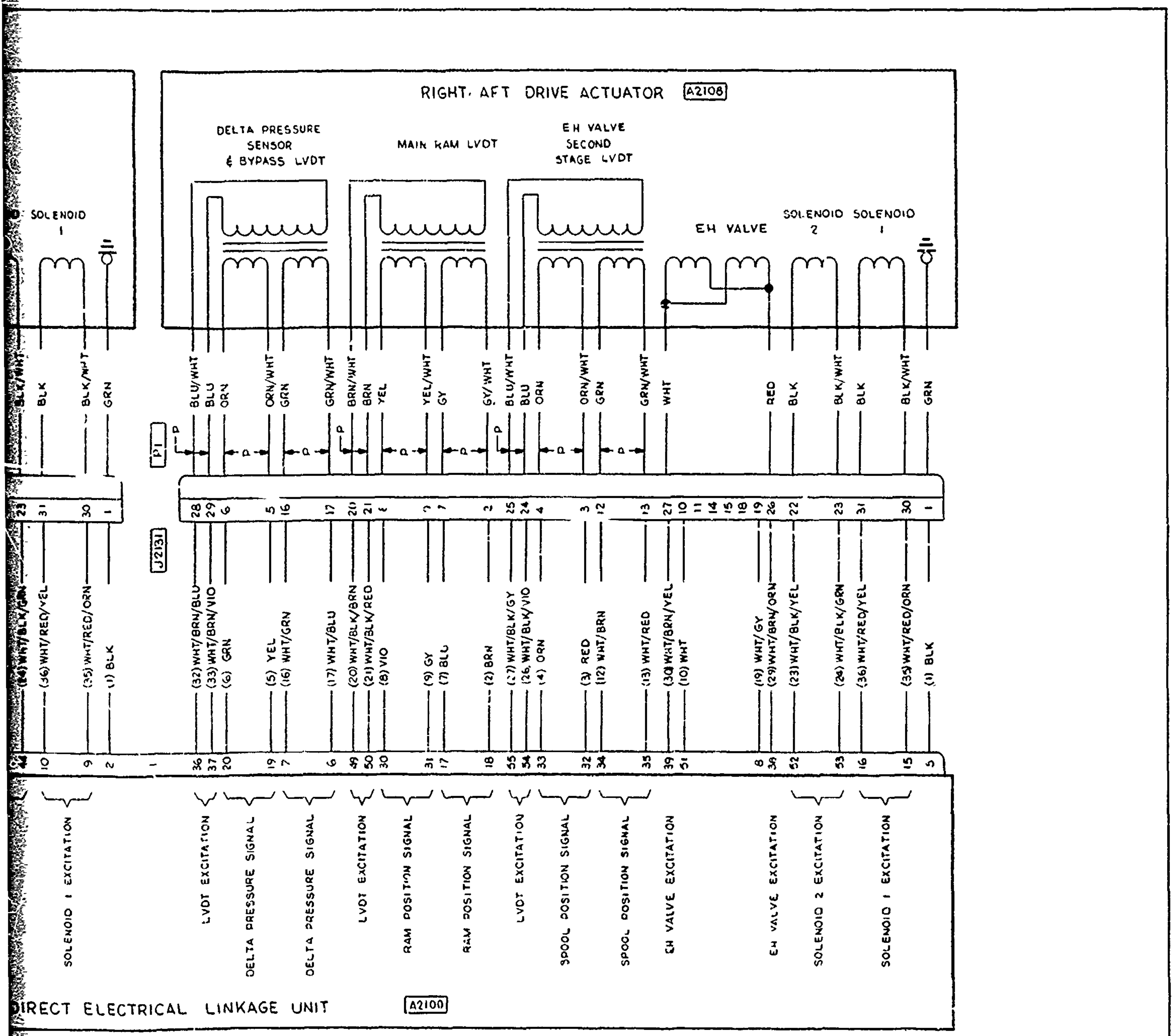

J5
J2
P2130
52 (BLK)
58 (WHT/BRN/GRN)
56 (WHT/BRN/BLU)
59 (WHT/RED/YEL)
57 (WHT/RED/ORN)
SHT. 1.1.1
SEE SH 1.1.9
SHT. 1.1.9
TB1
J7
P2136
109 (BLK)
110 (WHT/BRN/YEL)
115 (WHT/BRN/GRN)
113 (WHT/BRN/BLU)
117 (WHT/BRN/VIO)
112 (WHT/BRN/GY)
114 (WHT/RED/ORN)
116 (WHT/RED/YEL)
111 (WHT/RED/GRN)
A2110
DELS JUNCTION BOX



J5-DEL J BOX
J6 & J7-DEL UNIT

SIZE	CODE IDENT NO		
B	77272	SK 26744	
	SCALE NONE	REV 10-6-75	SHEET 1.1.7

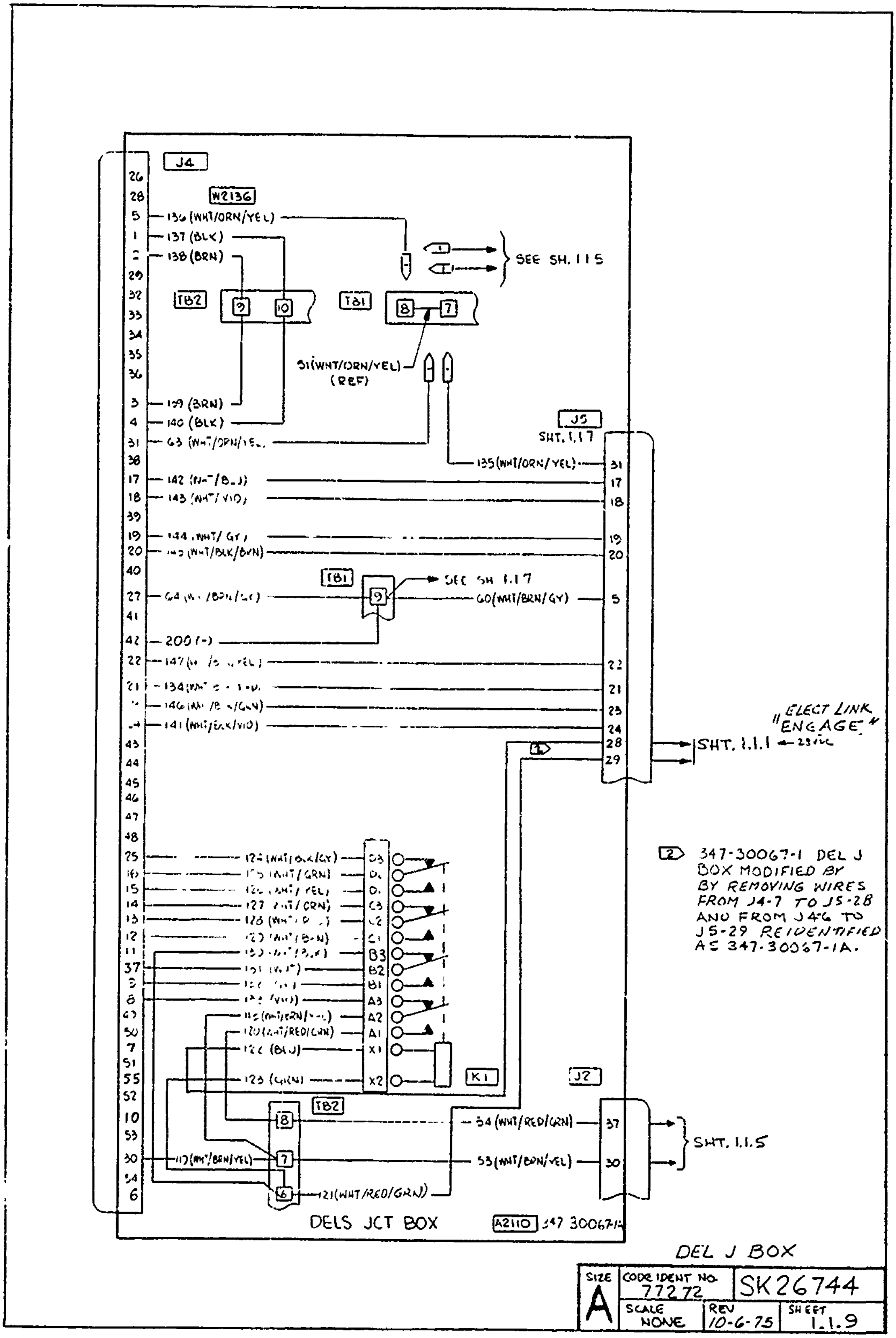

LEFT AFT DRIVE ACTUATOR
DELTA PRESSURE SENSOR & BYPASS LVDT
MAIN RAM LVDT
EH VALVE SECOND STAGE LVDT
EH VALVE
SOLENOID 2
SOLENOID 1
P1
J2130
W2115
P2118
J2131
J8
LVDT EXCITATION
DELTA PRESSURE SIGNAL
RAM POSITION SIGNAL
SPOOL POSITION SIGNAL
EH VALVE EXCITATION
SOLENOID 2 EXCITATION
SOLENOID 1 EXCITATION
J9
28VDC
28VDC RETURN
CHASSIS GND
DIRECT ELECTRICAL LINKAGE UNIT
P2150
F.B.W CONTROL PANEL
CB1

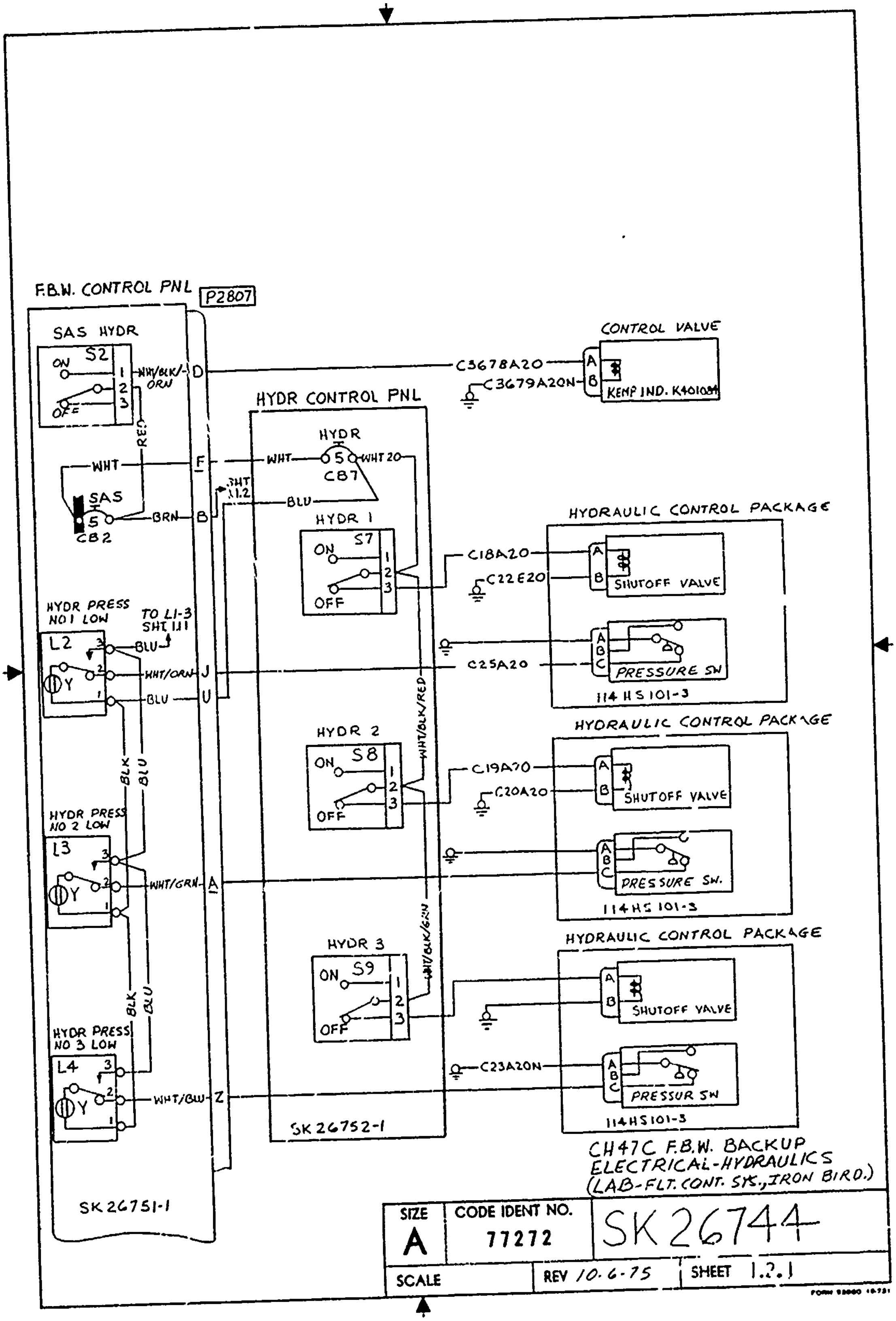


AFT DRIVE ACTUATORS TO DEL UNIT

SIZE	CODE IDENT NO.	
B	77272	SK26144
	SCALE NONE	REV	SHEET 118

2


J4
W2136
136 (WHT/ORN/YEL)
137 (BLK)
138 (BRN)
SEE SH. 1.1.5
TB2
TB1
51 (WHT/ORN/YEL)
(REF)
139 (BRN)
140 (BLK)
J5
SHT. 1.1.7
135 (WHT/ORN/YEL)
144 (WHT/GY)
SEE SH 1.1.7
60 (WHT/BRN/GY)
200 (-)
141 (WHT/BLK/VIO)
"ELECT LINK ENGAGE"
SHT. 1.1.1
347-30067-1 DEL J BOX MODIFIED BY BY REMOVING WIRES FROM J4-7 TO J5-28 AND FROM J4-6 TO J5-29 REIDENTIFIED AS 347-30067-1A.
122 (BLU)
123 (GRN)
K1
J2
54 (WHT/RED/GRN)
53 (WHT/BRN/YEL)
117 (WHT/BRN/YEL)
121 (WHT/RED/GRN)
SHT. 1.1.5
DELS JCT BOX
A2110 347 30067-1A
DEL J BOX
SIZE A
CODE IDENT NO. 77272
SK26744
SCALE NONE
REV 10-6-75
SHEET 1.1.9



F.B.W. CONTROL PNL
P2807
SAS HYDR
S2
ON
OFF
WHT/BLK/ORN
RED
WHT
SAS
CB2
BRN
SHT 1.1.2
BLU
HYDR PRESS NO 1 LOW
TO L1-3 SHT 1.1.1
L2
WHT/ORN
HYDR PRESS NO 2 LOW
L3
BLK
WHT/GRN
HYDR PRESS NO 3 LOW
L4
WHT/BLU
SK 26751-1
HYDR CONTROL PNL
HYDR
CB7
WHT 20
HYDR 1
S7
HYDR 2
S8
HYDR 3
S9
WHT/BLK/RED
WHT/BLK/GRN
SK 26752-1
CONTROL VALVE
C3678A20
C3679A20N
KEMP IND. K401034
HYDRAULIC CONTROL PACKAGE
C18A20
C22E20
SHUTOFF VALVE
C25A20
PRESSURE SW
114 HS 101-3
C19A20
C20A20
C23A20N
PRESSUR SW
CH47C F.B.W. BACKUP ELECTRICAL-HYDRAULICS (LAB-FLT. CONT. SYS., IRON BIRD.)
SIZE A
CODE IDENT NO. 77272
SK 26744
SCALE
REV 10-6-75
SHEET 1.2.1

9777-76